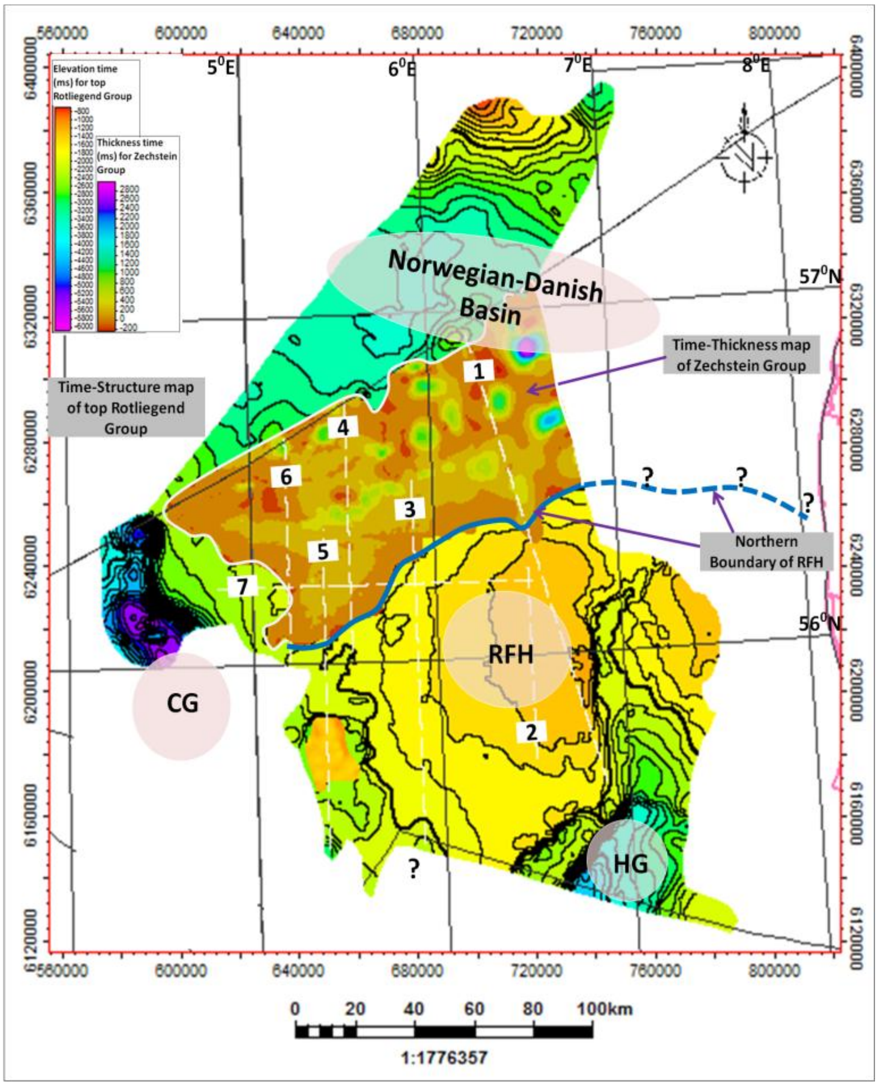
Master Thesis, Department of Geosciences

Late Carboniferous-Early Permian structural development of the Ringkøbing-Fyn High and adjacent Norwegian-Danish Basin

Muhammad Aftab Javed



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Master Thesis in Geosciences

Discipline: Petroleum Geology and Petroleum Geophysics

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Abstract

A grid of 2D regional seismic lines from six different surveys together with Bouguer gravity anomaly data and borehole data sets have been used to get an insight of the structural development of the Ringkøbing-Fyn High and the nearby Norwegian-Danish Basin.

The Ringkøbing-Fyn High consists of relatively shallow basement rocks as compared to the Norwegian-Danish Basin which is cut by the approximately north-south trending Horn Graben. The western fraction of the high is bounded by the Central Graben in the West and the Horn Graben in the East which is characterized by ESE-WNW to E-W to ENE-WSW to NE-SE trending extensional faults, displaying half-graben structural settings. Mainly normal faults belong to an early Permian rifting event based on the stratigraphic dating method. However, extensional faults related to a rifting phase older than Permian extension is limited to southwestern part of the Ringkøbing-Fyn High. The normal faults over the Ringkøbing-Fyn High and the adjoining Norwegian-Danish Basin can be classified as planar to slightly curved to listric in geometry. Mostly extensional faults are restricted below the top Rotliegend Group with minor reactivation in the Triassic and the mid-late Cretaceous. The Triassic reactivation is concentrated in the proximity of the Horn Graben.

The thickness of the Palaeozoic sedimentary succession over the Ringkøbing-Fyn High is much greater in the northern half-grabens where it reaches up to 1500 (ms) twt while towards the southern half-grabens it reduces to 450 ms (twt). This varied thickness is accredited to differential uplift of the Ringkøbing-Fyn High. During uplift, maximum erosion of the Palaeozoic strata took place in the central part of the Ringkøbing-Fyn High displaying a dome shape while the northern side experienced relatively less erosion. Several regional unconformities have also been interpreted in the study area which include Rotliegend, Saalian, Base Jurassic and Base Cretaceous unconformities.

Seismic interpretation shows that early Permian rifting and uplift of the Ringkøbing-Fyn High might have been contemporaneous in the study area. This positive structure remained relatively uplifted until early late-Triassic while the Norwegian-Danish Basin experienced subsidence after rifting which is inferred from the thick late Permian and Triassic succession. A thin late Triassic succession is found to be present at places over the Ringkøbing-Fyn High showing the start of deposition over the structure. The uplift of the Ringkøbing-Fyn High is attributed to the Skagerrak Centered Large Igneous Province (SCLIP) due to its best chronological relevance with stratigraphic dating of the faults. Later in late Cretaceous, less thickness of the Chalk Group over the Ringkøbing-Fyn High demonstrates that the structure has tolerated slight uplift during this time interval due to unknown reason. The study also constrains the northern extent of the Ringkøbing-Fyn High based on the Zechstein salt termination line and extensional faults on the northern flank of the Ringkøbing-Fyn High.

Acknowledgement

I express special thanks and inner heart gratitude to my supervisors Dr. Michael Heeremans and Prof. Jan Inge Faleide for their kind supervision and guidance during the whole work. Their meaningful discussions kept me on the track for carrying out this research work.

This dissertation would have been impossible without the availability of the seismic and Bouguer gravity anomaly data sets. Fugro-Geoteam, TGS and the Danish Geological Survey (GEUS) deserve a special gratitude for allowing to utilize the seismic data sets.

I am grateful to my loving family and friends especially my elder brother Muhammad Azhar Iqbal who in one way or another has been source of encouragement and inspiration in my academic career and whole through my life.

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Muhammad Aftab Javed

Contents

CHAPTER 1

INTRODUCTION

1.1. Introduction to the study area

The North Sea is characterized by complex geological history comprising numerous rifting phases with major extensions in the Triassic and the Jurassic (Ziegler, 1977; 1982; Bishop, 1996). The Ringkøbing-Fyn High is a NWW-ESE trending positive structure in the North Sea which segregates the North German Basin in the South and the Norwegian-Danish Basin in the North (Zhou and Thybo, 1997). The Ringkøbing-Fyn High has been shaped by different fault systems (Scheck et al., 2002) and various theories for its origin have been suggested earlier (Zeigler, 1982; Dewey, 1982; Donato et al., 1983; Cartwright, 1990). This High is cut by the Horn Graben in the central part and is divided into the western and the eastern fractions. The present work is carried out on the structural evolution of the western part which is bounded by the Central Graben in the West and the Horn Graben in the East.

The Norwegian-Danish-Basin is located in the region of the southern tip of Norway (Ebbing and Olesen, 2010) which together with the Ringkøbing-Fyn High are considered the tectonic elements of the southeastern North Sea (Nielsen et al., 2005). Geographically, the Norwegian-Danish Basin lies among the Horda Platform in the North (Hospers et al., 1988), Baltic Shield and Fennoscandian Border Zone towards northeast, the Ringkøbing-Fyn-Møn basement highs (RFMH) towards southwest and the North-South trending Central Graben in the West. It is a depression having about 500 km length and 150- 250 km width. In the deepest parts, 5-10 km sedimentary sequence of the late Palaeozoic, the Mesozoic and the Cenozoic ages is present having a NW-SE strike direction. The Norwegian-Danish-Basin is one of the biggest basins in the North Sea (cf. Ziegler, 1990; Glennie, 1990; Frederiksen et al., 2001). The location of study area is shown in figure 1.1.

1.2. Objective

The main objective of the study is to analyze the late Carboniferous- early Permian structural development of the Ringkøbing-Fyn High and adjacent area of the Norwegian-Danish basin with special emphasis on the timing of the fault activity along the northern margin of the Ringkøbing-Fyn High. The study integrates observations on structural evolution, fault geometries, reactivation along the fault planes and thickness variations of the sedimentary succession. The detailed structural analysis of the pre upper-Permian faults is done by studying vertical and horizontal fault geometries.

1.3. Hydrocarbon Prospect

In the central North Sea, the upper Palaeozoic sequence has not been the interest of the oil and gas industry from hydrocarbon resource point of view. However, the Permian and the Carboniferous succession of the Southern Permian Basin contain large reserves of gas and gas-condensate (Kombrink et al., 2010). Because of large depth, the Carboniferous source rocks are considered to be post-mature for the hydrocarbon generations. Therefore, it is a general perception about the Permian rocks in the central North Sea that they are hydrocarbon deficient. But, the Permian sediments contain hydrocarbons generated from the down faulted Jurassic rocks near the Central Graben (Glennie et al., 2003). In the Norwegian-Danish Basin, the upper Permian salt deposits of the Zechstein Group have strongly influenced the younger strata structurally and stratigraphically. The faulted and fractured cap rocks above the salt diapirs have hosted commercial hydrocarbon reservoirs in the North Sea (Bishop, 1996).

Fig. 1.1. Location map of the study area shown in the black box (modified from www.agu.org). The map is created by Norman Einstein.

1.4. Methods and tools employed

The present study has been accomplished by utilizing the 2-D seismic reflection data, Bouguer gravity anomaly data and well data sets. To achieve the optimum results interpretation of the seismic data has been supported by the Bouguer gravity anomaly data and the borehole data sets. A grid of 2-D regional seismic lines has been interpreted using the Petrel^{TM} software (Schlumberger). Seismic interpretation was initiated with the well data by seismic to well tie that was followed by the detailed stratigraphic and structural interpretation of the study area. In order to achieve the objectives of the study, interpreted faults and reflections were used to construct the fault maps, time-structure maps and time-thickness maps.

CHAPTER 2

REGIONAL TECTONIC AND STRATIGRAPHIC FRAMEWORK

2.1. Regional Tectonic Evolution

The Norwegian-Danish Basin has suffered many stages of deformation since the Precambrian times (Sandrin et al., 2009). Two significant tectonic events in north-west Europe are well known, the Caledonian and the Variscan Orogenies. Then, during the Mesozoic rifting, the Trans-European fault zone and Thor Suture Zone have been reactivated in the areas of central Europe and the central part of the North Sea. But, the Caledonian structures of the North Sea and west of the Britain Isles do not show pronounced extension during Mesozoic (Coward et al., 2003). Regional tectonic and structural elements are shown in figure 2.1. A brief description of the tectonic history in different time intervals is given below:

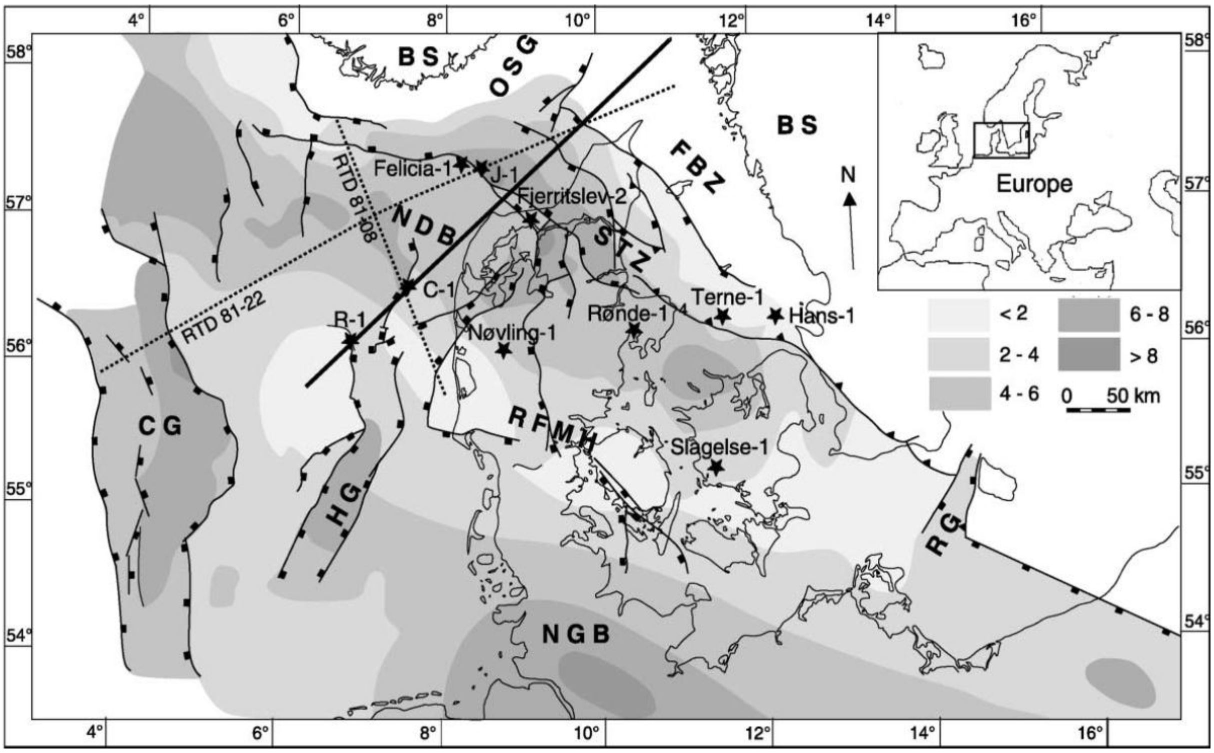


Figure. 2.1. Main tectonic and structural elements in the southeastern North Sea. NDB: Norwegian-Danish Basin, BS: Baltic Shield, OSG: Oslo-Skagerrak Graben, FBZ: Fennoscandian Border Zone, CG: Central Graben, HG: Horn Graben, RFHM: Ringkøbing-Fyn-Møn-High, RG: Rønne Graben, NGB: North German Basin (after Frederiksen et al., 2001).

2.1.1. Pre-Devonian plate tectonic history

About 1100 Ma ago in the late Meso-Proterozoic times, the Rodinia Supercontinent formed (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991; Torvik et al., 1996) which started breaking up around 750-725 Ma ago (Powell et al., 1993; Storey, 1993; Dalziel et al., 1994; Soper, 1994a, b; Torsvik et al., 1996). Then Laurentia and Baltica started drifting by rotating clockwise and moving southwards about 600 Ma ago following the separation between them resulting in the Iapetus Ocean. Laurentia started drifting back to low latitudes very fast at 20cm/ year in the latest Precambrian times and stayed there most of the Paleozoic time. In the late Precambrian to early Ordovician Baltica's position was at intermediate to high southerly latitudes after that it started drifting northward in anticlockwise rotation to close the Iapetus Ocean (Bassett, 2003). The collision of Laurentia with the Baltica and Avalonia plates in Silurian times is well documented (*fig. 2.2*) (Torsvik , 1998).

2.1.2. Caledonian Orogeny

The ‘Caledonian Deformation Front’ is a suture between Baltica and micro-continent Avalonia in the southeastern North Sea (Abramovitz & Thybo, 1998), indicating the Tornquist Sea closure (Cocks and Fortey, 1982; Pharaoh, 1999). Eastern Avalonia collided with Baltica first and then in latest Ordovician to early Silurian both collided with Laurentia. The collision between Baltica and eastern Avolania (Bassett, 2003) resulted in metamorphic facies around 450 Ma ago represented by amphibole facies on the Mid North Sea High (Frost et al., 1981; Pharaoh, 1999). The Iapetus Ocean closed further as a result of collision between the western Norwegian sector of Baltica and the Scotland/ Greenland part of the Laurentia. The Caledonian collision across the North Sea in Norway occurred between Laurentia and Scandinavia. It started in the Ordovician with obduction of material of the island arc but south-easterly directed thick-skinned overthrusting persisted up to Silurian (Coward et al., 2003).

The Caledonian collision probably took place by mid-Silurian time based on the stratigraphic studies (Soper & Woodcock, 1990; Soper et al., 1992b), but prior to late early-Devonian (Soper et al., 1987; McKerrow, 1988; Soper et al., 1992b). The Caledonian structures may have been obscured by rifting events that occurred later in the central North Sea (Abramovitz et al., 1997)

2.1.3. Devonian

The North Sea has experienced extension during Devonian (Zielgler, 1990a; Viejo et al., 2002), while in the Kattegat area a small tectonic activity occurred during Devonian to early Carboniferous (Mogensen, 1994). There was regression in the early Devonian period accompanying stages of uplift and broad-scale folding. These events were followed by rapid subsidence with possible minor rifting and then marine conditions during the late Devonian prevailed. Similarly rifting happened in the southern North Sea (Coward et al., 2003).

2.1.4. Carboniferous

The Ribblesdale fold belt in northern England formed at the end of Carboniferous as a result of inversion of the early Carboniferous basins. Also, this was the time of the Mid North Sea High to uplift (Coward et al., 2003). The reworking of the Caledonian structures during Variscan Orogeny created local thickening of the crust and uplift. The structures in Europe formed during the late Caledonian Orogeny were tightened due to Carboniferous Variscan tectonics (Coward et al., 2003). A large magmatism along with transtension movement during late Carboniferous-early Permian, created e.g. Horn Graben (HG), Oslo Graben (OG) and Brande Graben (BG) (Sandrin et al., 2009).

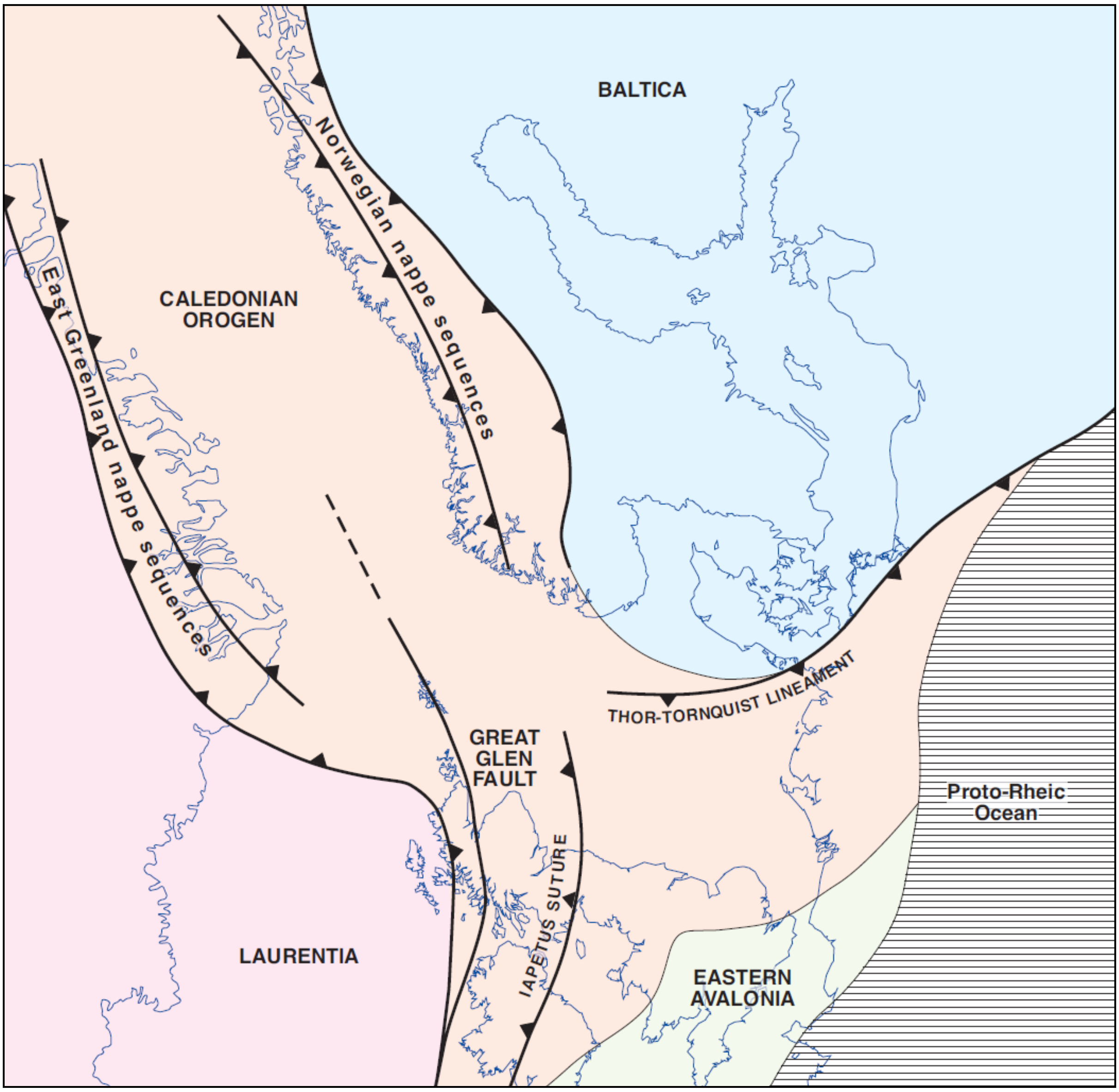


Figure. 2.2. Early Palaeozoic positions of the plates in the North Sea area. This is the position of the three blocks of Laurentia, Baltica and Eastern Avalonia by approximately mid-Silurian times but Laurentian and Baltica converged transpressionally until mid-Devonian (modified from Bassett, 2003).

2.1.5. Variscan Collision

Gatliff et al. (1994) suggested that the Variscan Orogeny started farther south of Caledonian Deformation Front in the Devonian, shifting towards north and ended in the late Carboniferous. On the contrary, other authors proposed early Devonian to mid-Carboniferous ages for the Variscan collision in Europe between Laurussia (Baltica, Laurentia & Avolania) and Gondwana (Bard et al., 1980; Behr et al., 1984; Matte, 1986; Franke, 1989 a, b; Rey et al., 1997). The NW- overlapping of crustal blocks and magmatic arcs on the Laurentia foreland resulted in Variscan structures in NW Europe. The closure of the Iapetus Ocean generated a new Rheic Ocean which was closed due to Variscan collision associated with ophiolites in the inner Variscan belt. The Trans-European Fault Zone marks the lateral boundary of the Variscan Bohernian massif (Ziegler, 1990; Coward, 1995). Variscan tectonics generated NW-verging thin-skinned fold and thrust belts in SW Britain (Shackleton et al., 1982; Coward, 1995).

2.1.6. Permian

After the Variscan Orogeny, the compressional forces were substituted by extensional tectonics in north-western Europe (Deegan and Scull, 1977). Late Carboniferous - early Permian is the period of extensive volcanism and crustal stretching associated with thermal subsidence and growth of sedimentary basins which include the southern and northern Permian Basins (Ziegler, 1982, 1990; Glennie 1998; Van Wees et al. 2000; Frederiksen et al. 2001; Glennie et al. 2003; Neumann et al. 2003; Heeremans & Faleide, 2004). These volcanic and magmatic intrusions of the late Carboniferous-early Permian age are dated in the Oslo Graben, (Sundvoll er al. 1990; Torsvik et al. 1998).

Towards Norway and southern Sweden, the age of the widespread magmatic activity is found late Carboniferous to early Permian (Frost et al., 1981; Neuman et al., 1992; Sandrin et al., 2009). After volcanism and magmatic intrusions under the North Sea, thermal subsidence was responsible for the Rotliegend and Zechstein basins. In the late Permian, melting of the Permo-Carboniferous ice of Gondwana resulted into eustatic sea level rise. As a result of marine transgression, the Zechstein Sea generated across northern and central Europe. Later on deposition of the Zechstein salt took place in the local Permian Salt basins (Coward et al., 2003).

2.1.7. Mesozoic Tectonic Evolution

Permo-Triassic is the transformation period of the Caledonian and the Variscan orogenic belts to continental extension resulting into rift basins in the tectonic regime of NW Europe (Coward, 1995). The Permian structural patterns were superimposed by a graben system in the central and northern North Sea which dissected the northern Permian Basin and ruptured the Mid North Sea-Ringkøbing-Fyn-High (Coward et al., 2003). Beach (1987) proposed north-west to southeast direction of extension and argued that right-lateral shear system resulted in pull apart structures including the Horn Graben, the Central Graben and the Bamble Graben. According to Coward (1995) extension directions are unknown all over the North Sea but the direction for the Triassic faults of Central Graben was north-east to south-west.

Another rifting phase occurred in late Jurassic in the central and northern North Sea during which mostly oblique slip extension took place along the pre-existing Triassic faults. In the earliest Cretaceous, normal faults were active in the central North Sea and northern North Sea with continuous deposition of wedge shaped clastic sediments along the fault escarps. Extension came to the end during early Cretaceous, following the thermal subsidence in the late Cretaceous and syn-rift deposits were covered by transgression strata, to make Base Cretaceous Unconformity (Coward et al., 2003).

2.2. Regional Stratigraphic Framework

Pre-Devonian basement rocks under the central North Sea consist of different rock types such as igneous rocks, meta-sedimentary and low to high-grade metamorphic facies. (Bassett, 2003). The metamorphic basement rocks with ages of 480 to 430Ma cover almost the whole of the North Sea (Frost et al., 1981). The regional stratigraphy of the central North Sea is given below.

2.2.1. Silurian Old Red Sandstone

The pre-Devonian lower facies of the Old Red Sandstone have been confirmed in the North Sea by wells. Their existence at places shows post-early Paleozoic erosion rather than non-deposition (Bassett, 2003). In the Kattegat and the Tornquist Zone, late Silurian to Rotliegend succession is also missing in Terne-1 well (Mogensen, 1994). Many granitic intrusions of different ages are also present in the North Sea region. Most of the central North Sea may have low-grade metamorphic rocks of the Caledonian origin (Gatliff et al, 1994).

2.2.2. Devonian

A widespread Old Red Sandstone facies mostly of the Devonian age is present over most of the North Sea which is part of the syn-Caledonian orogenic to late-orogenic molasse sedimentary rocks. Devonian strata have been encountered in more than 150 wells in the central and northern North Sea which is a thin Red bed Sandstone and in many wells basement is encountered without Devonian Red beds (Marshall & Hewett, 2003). The Devonian stratigraphy is well documented in the west of the study area towards the Mid North Sea High and Central Graben is shown in figure 2.3.

2.2.2.1. Lower Old Red Group

The deposition of the Old Red Group took place due to uplifting and erosion of part of the Caledonides. The base of the Group is marked by an angular unconformity (Marshall & Hewett, 2003). Gatliff et al. (1994) used available wells and geophysical data and stated that the lower part of the Old Red Group is very thin or absent in the central North Sea and Mid North Sea High. In the same way, middle Old Red Sandstone Group is confined to the Orcadian Basin and the closely offshore areas (Marshall & Hewett, 2003).

2.2.2.2. Upper Old Red Group

The upper Old Red Group consists primarily of fluvial sandstones. The Buchan Formation of the upper Devonian age was deposited in the north of the Mid North Sea High and along the Highland boundary. Then deposition of the unit took place in the Midland Valley of Scotland and in the nearby offshore areas somewhere in late Devonian times. Upper Old Red Group can be as young as Carboniferous. In case of absence of the Carboniferous rocks, it is very difficult to separate the Devonian strata (Rory or Buchan formation) from the Permian Rotliegend Group because of similar behavior of the sandstones as Rotliegend group is mostly derived from Devonian sediments. In the Norwegian sector, the Embla field has produced Devonian reservoirs, also four other fields have produced in UK sector (Marshall & Hewett, 2003).

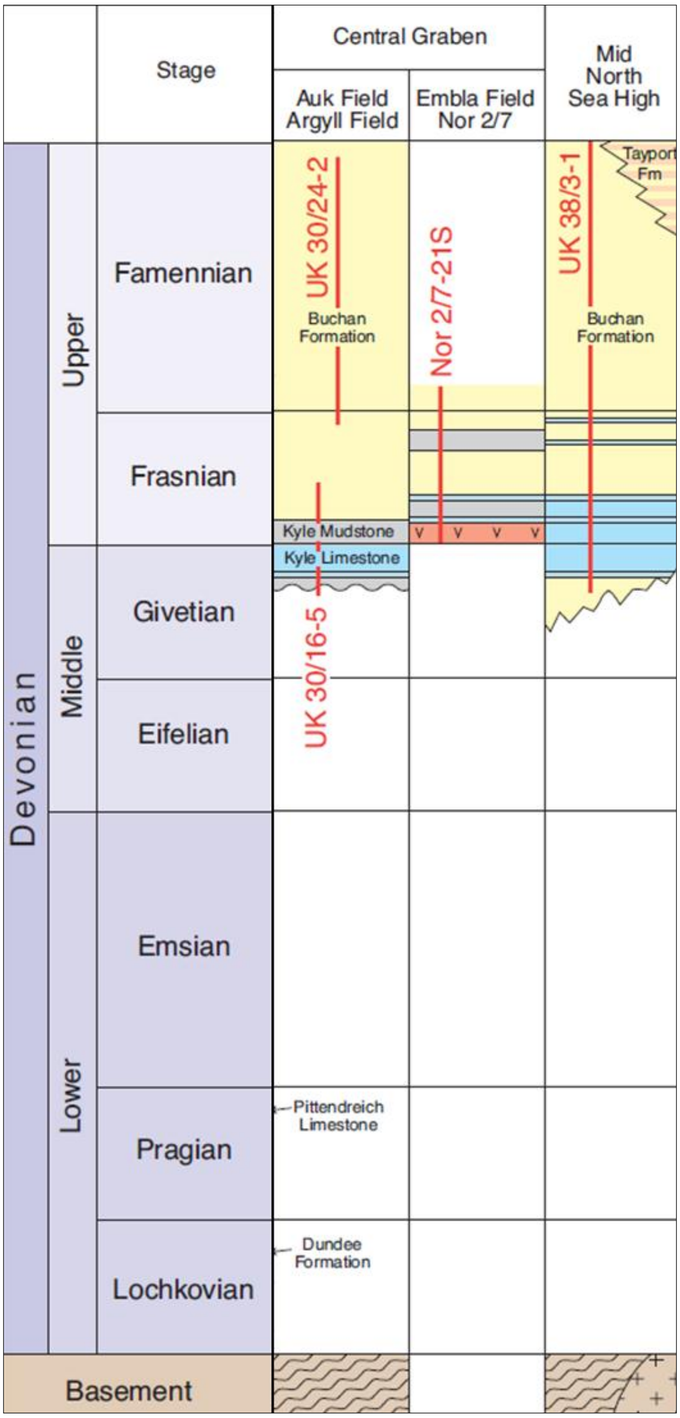


Fig. 2.3. Devonian stratigraphy of the Central Graben and the Mid North Sea High (modified from Marshall & Hewett, 2003).

2.2.3. Carboniferous

After the deposition of continental Red beds of the Devonian age, there was more distributed deposition of fluvial, deltaic, marine and continental sediments. Mostly, the Carboniferous rocks drilled in the north of Mid North Sea High and the Ringkøbing-Fyn-High are of early Carboniferous age (*fig. 2.4*) (Bruce & Stemmerik, 2003). Upper Carboniferous strata are limited to UK Quadrant 31. In the late Carboniferous, extensive volcanism occurred in the Oslo Graben, Central Scotland and Northern England. The volcanic sequence encountered in well 39/2-4 in the central North Sea is named Inge Volcanics Formation (Cameron, 1993) and is a part of the lower Rotliegend Group of late Carboniferous-early Permian age (Glennie, 1990; Plein, 1995; Heeremans et al., 2004a).

This volcanic activity also occurred at many other places such as Sorgenfrei-Tornquist Zone, Skagerrak Graben and North Sea which also covers the Horn Graben and the Central Graben (Heeremans et al., 2004b).

Also, volcanics in the Skagerrak Graben have not been proved by drilling but seismic interpretation and unpublished gravity and magnetic data indicate their presence (Heeremans and Faleide, 2004; Heeremans et al., 2004b). The upper Carboniferous-Permian sedimentary rocks are considered to be present in the eastern and central Norwegian-Danish Basin as they are present in Oslo Graben, Sorgenfrei-Tornquist Zone (Heeremans et al., 2004b) and Central Graben (Stemmerik et al., 2000; Heeremans et al., 2004b).

Upper Carboniferous coals are mainly the source of gas field in the southern North Sea, but their importance is limited in the central and northern North Sea because of deficiency of the coal-bearing strata. Carboniferous rocks are also present on the Mid North Sea high and the southern Central Graben (Bruce & Stemmerik, 2003). The Carboniferous stratigraphy of the Mid North Sea High and the Danish North Sea is shown in figure 2.4.

2.2.4. Permian

In northwestern Europe, Permian rocks are categorized into Rotliegend and Zechstein Groups and these groups can be documented in the central North Sea (Deegan and Scull, 1977). The Permian stratigraphy of the Norwegian-Danish is shown in figure 2.6.

2.2.4.1. Rotliegend Group

The Rotliegend Group is not well known in the northern Permian Basin as compared to the southern Permian Basin because of fewer wells drilled and deficiency of outcrops. The succession known as Rotliegend Group in the Norwegian-Danish Basin and the Danish Central Graben was deposited in the northern Permian Basin situated on the northern side of the Ringkøbing- Fyn-Mid-North-Sea Highs (Stemmerik et al., 2000). The Permian stratigraphy of the central North Sea is shown in figure 2.5.

2.2.4.2. Lower Rotliegend Group

The lower Rotliegend rocks are of volcanic origin but they also have few fluvial and lacustrine sedimentary sequences (Cameron, 1993; Plein, 1995; Martin et al., 2002; Heeremans et al., 2004b). These volcanics present in the Norwegian-Danish Basin are known as the Karl Formation which also includes volcanoclastic and sedimentary fill in the Danish part of the northern Permian Basin. Three different volcanic eruption events in the Danish

North Sea are reported having ages of 300-288 Ma, 281 ± 8 to 276 ± 14 Ma and 269 ± 4 to 261 ± 4 Ma respectively (Stemmeriket al., 2000).

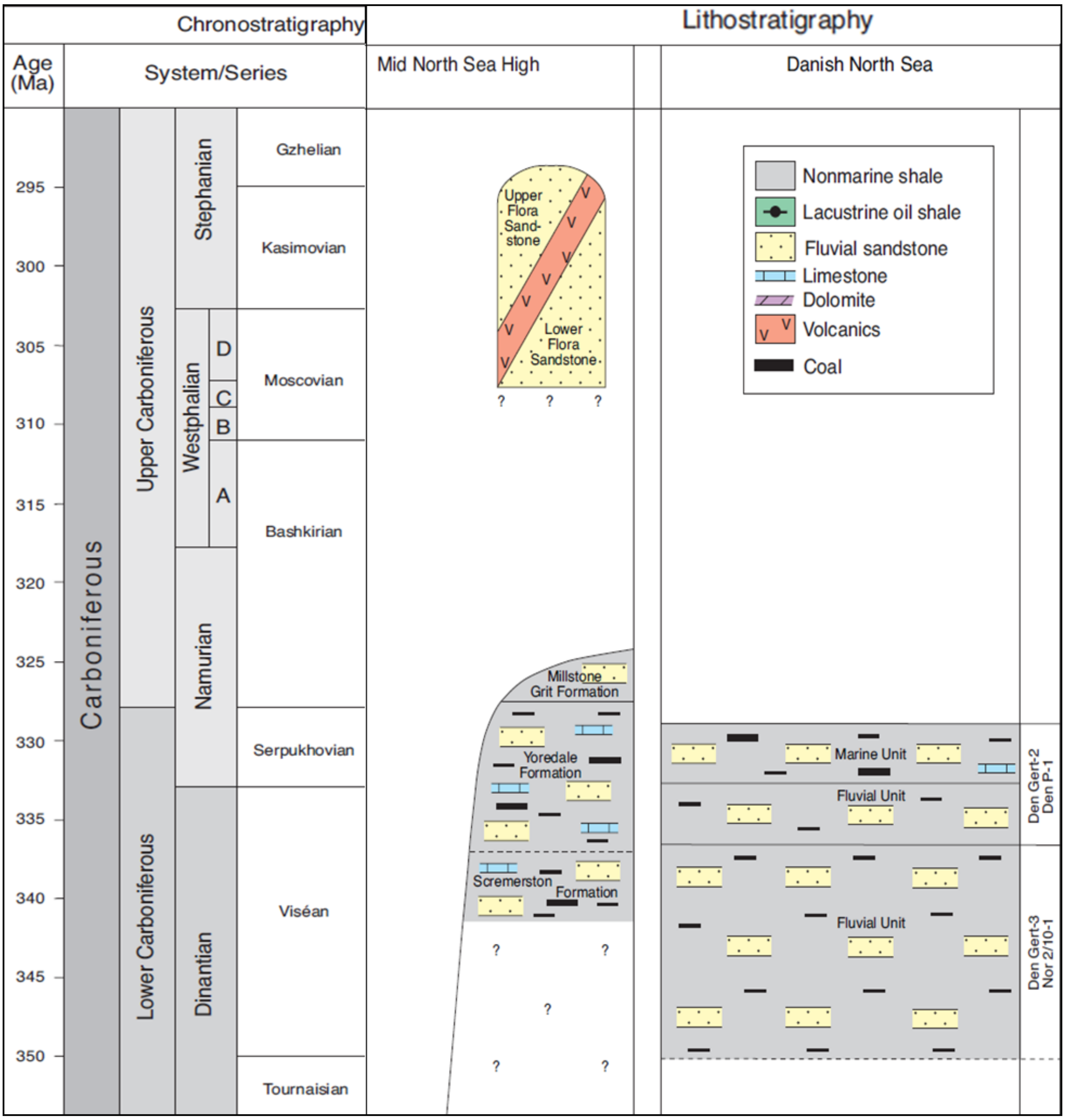


Figure. 2.4. Carboniferous lithostratigraphy of the Mid North Sea High and the Danish North Sea (modified from Bruce & Stemmerik, 2003).

The volcanics of youngest age were encountered in the Norwegian-Danish Basin and in the western half of the Danish Central Graben. In the well R-1 (for location see *fig. 2.1*), 678 m of Rotliegend volcanic rocks were drilled and the base of the volcanics was still not encountered (Frederiksen et al., 2001).

The volcanic sequence seen in well 39/2-4 in the central North Sea is named Inge Volcanics Formation (Cameron, 1993; Heeremans et al., 2004a). These volcanics are overlain by fluvial, lacustrine, aeolian sandstones and Sabkha facies locally. Rotliegend sequences have inconsistent thickness as it is recorded 525m in the well UK 29/18-1. Towards the Danish and the Norwegian sides, thicknesses of 380m in the well Nor 2/1-7 and 369m in the well Elna-1 are reported. Volcanic rocks of the Permian Karl Formation occupy an area generally to the east of the Central Graben and the Ringkøbing-Fyn-High and to Norway which includes the Oslo Graben as well. The composition of the oldest volcanics in the Danish wells C-1 and R-1 is andesitic and rhyolitic (Glennie et al., 2003).

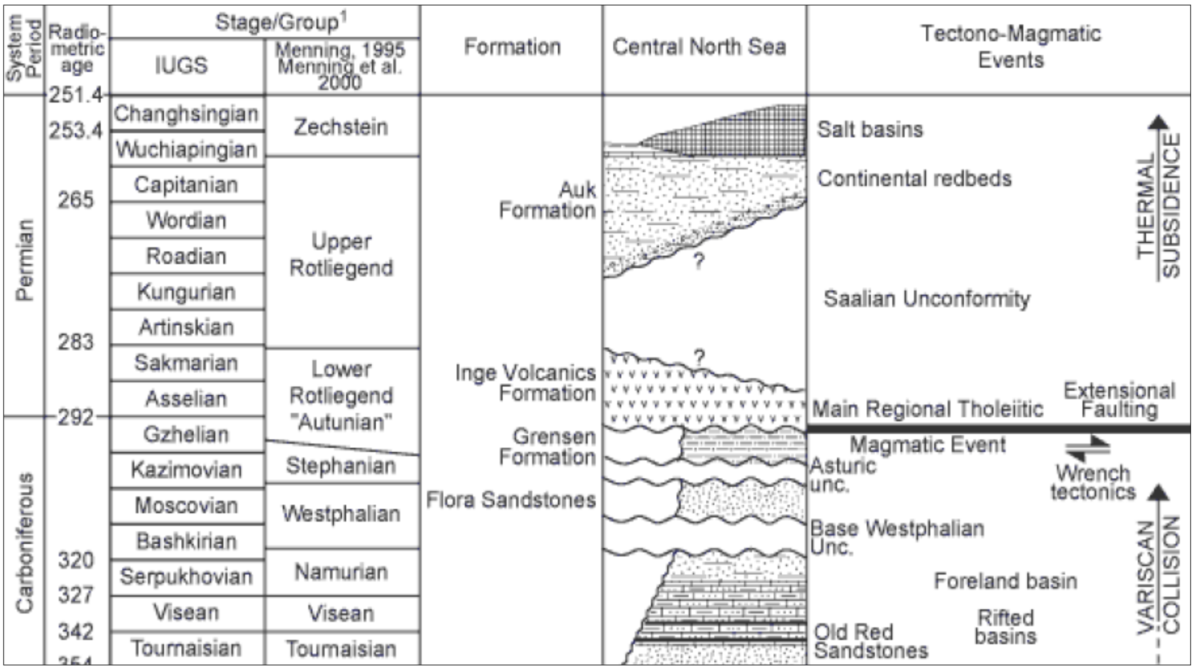


Figure. 2.5. The chart shows the Carboniferous-Permian stratigraphy and tectonics in the central North Sea. The time scales are taken from Menning (1995) and Menning et al., (2000) and official IUGS time scale is used as a reference (modified from Heeremans et al., 2004a).

2.2.4.3. Upper Rotliegend Unit

This unit is totally of sedimentary origin, composed of sandstones and claystones having large extent in the north of the Mid North Sea High and the Ringkøbing-Fyn-High. Local fluvial conglomeritic sandstones may have been generated from the Old Red Sandstone rocks that are lying at the base of the unit. An input from the Caledonian mountains of Scandinavia and Scotland with small contribution from the Mid North Sea High and the Ringkøbing-Fyn-High is possible. Sediments deposited by lakes or sabkhas are called Fraserburgh Formation which include siltstones and clay stones, intermingling with the Auk Formation (Glennie et al., 2003). Reworking of the unconsolidated fluvial sediments by wind has deposited aeolian sandstones. These reddish brown to grey sandstones of Permian age are named Auk Formation which is lying unconformably over the Devonian rocks (Deegan and Scull, 1977; Stemmerik et al, 2000). Towards the Mid North Sea High, this desert sandstone of the Auk Formation is overlying the Inge Volcanics (Cameron, 1993; Martin et al., 2002). The extent of the post-rift strata in the Danish waters of the Danish-Norwegian Basin is limited which is observed in three wells Ibenholt-1, D-1, and Elna-1 (Stemmerik et al., 2000).

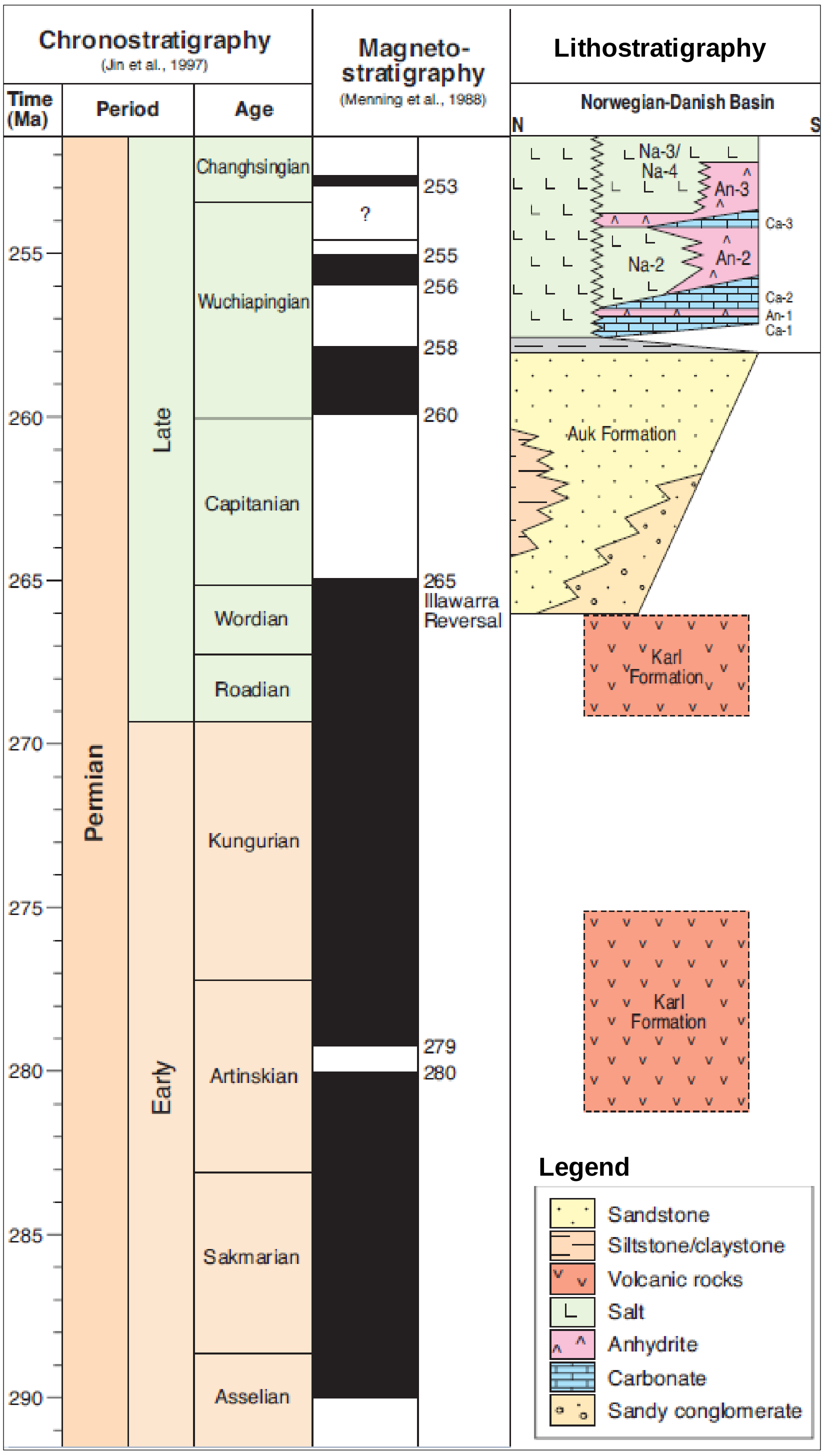


Figure. 2.6. Permian Stratigraphy of the Norwegian-Danish Basin (modified from Glennie et al., 2003).

2.2.4.4. Zechstein Group

Deegan & Scull (1977) stated that during the deposition of the upper Permian Zechstein group configuration of the the central North Sea was analogous to during the Rotliegend Group.

Glennie (1998) stated that depositional cycles of the Zechstein Group were associated with global sea level changes. The Ringkøbing-Fyn-High and the Danish Central Graben areas show a hiatus during the deposition of the Zechstein group (Stemmerik et al, 2000).

2.3. Structural Elements

The main structural elements in the study area are as follows:

2.3.1. Central Graben (CG)

The Central Graben represents the southern arm of the North Sea rift striking at NNW-SSE direction which passes through the UK, Norwegian, Danish, West German and Dutch sectors of the North Sea. The Central Graben experienced extension during both the Trissic and Jurassic (Roberts et al. 1990). The Central Graben comprises basement deformed by planar normal faults having large offsets which make a typical horst and graben system. Over the basement Zechstein salt of nonconstant thickness and Triassic-Recent successions are present respectively (Bishop, 1996). The thickness of the Triassic sedimentary strata in the Central Graben exceeds beyond 4 km. The Central Graben suffered rapid but asymmetric subsidence (Coward, 1995).

2.3.2. Ringkøbing-Fyn-High (RFH)

The Ringkøbing-Fyn-High is characterized by an area of shallow crystalline basement and occupies a thin cover of the Mesozoic and Tertiary rocks (Clausen and Pedersen, 1999). It is characterized by WNW-ESE trending series of rhombohedral horst massifs (Cartwright, 1990). The deformational front for the Scandinavian Caledonides might be denoted by the Else Duplex (westerly dipping) inside the Ringkøbing-Fyn-High (Gatliff et al, 1994). There is evidence that basement rocks in well Per-1 (*fig. 2.7*) show Caledonian overprint. These sparse samples of the crystalline basement show that a key crustal province boundary should be here on the Ringkøbing-Fyn-High (Cartwright, 1990).

2.3.3. Horn Graben (HG)

The Horn Graben is located about 50-100 km west from the western coast of Denmark about. It transects the Ringkøbing-Fyn-High in the NNE-SSW direction (Beha et al., 2008). On the basis of structural behavior, the Horn Graben can be subdivided into southern and northern segments having character of the half-grabens merging into Norwegian-Danish Basin further in the north (*fig. 2.7*) (Vejbæk, 1990). The Horn Graben is an eastward dipping half-graben in the north and it is dipping towards west in the south (Clausen and Korstgård, 1994; Vejbæk, 1990; Beha et al., 2008). The major basement faults marking the Horn Graben show a mean NNE-SSW rift axis (Cartwright, 1990).

2.3.4. Norwegian-Danish Basin

The Norwegian-Danish Basin is located in eastern part of Northern Permian Basin (Frederiksen et al., 2001). The crust under the Norwegian-Danish Basin is thin in contrast to neighboring areas of the Baltic Shield, the Fennoscandian Border Zone and the Ringkøbing-Fyn-Møn High based on deep seismic evidences from the areas of southern Scandinavia (EUGENO-S Working Group, 1988; Ballin, 1990; Kinck et al., 1993; Thybo, 2000, Frederiksen et al., 2001). Precambrian basement rocks are supposed to be present under the Norwegian-Danish Basin analogous to Sveconorwegian units of the nearby southwestern Baltic Shield (Frederiksen et al., 2001).

During the late Palaeozoic, thinning of the lithosphere occurred with continental extension in the Tornquist area and this thinning of the lithosphere was accommodated by mantle-derived magma, which resulted into uplift and subsequent erosion of the top sedimentary layers. It is believed that a later cooling stage is responsible for the formation of the Norwegian-Danish basin due to thermal contraction and sediment loading. The hot magma intrusions at different levels are important in subsidence history (Sandrin et al., 2009).

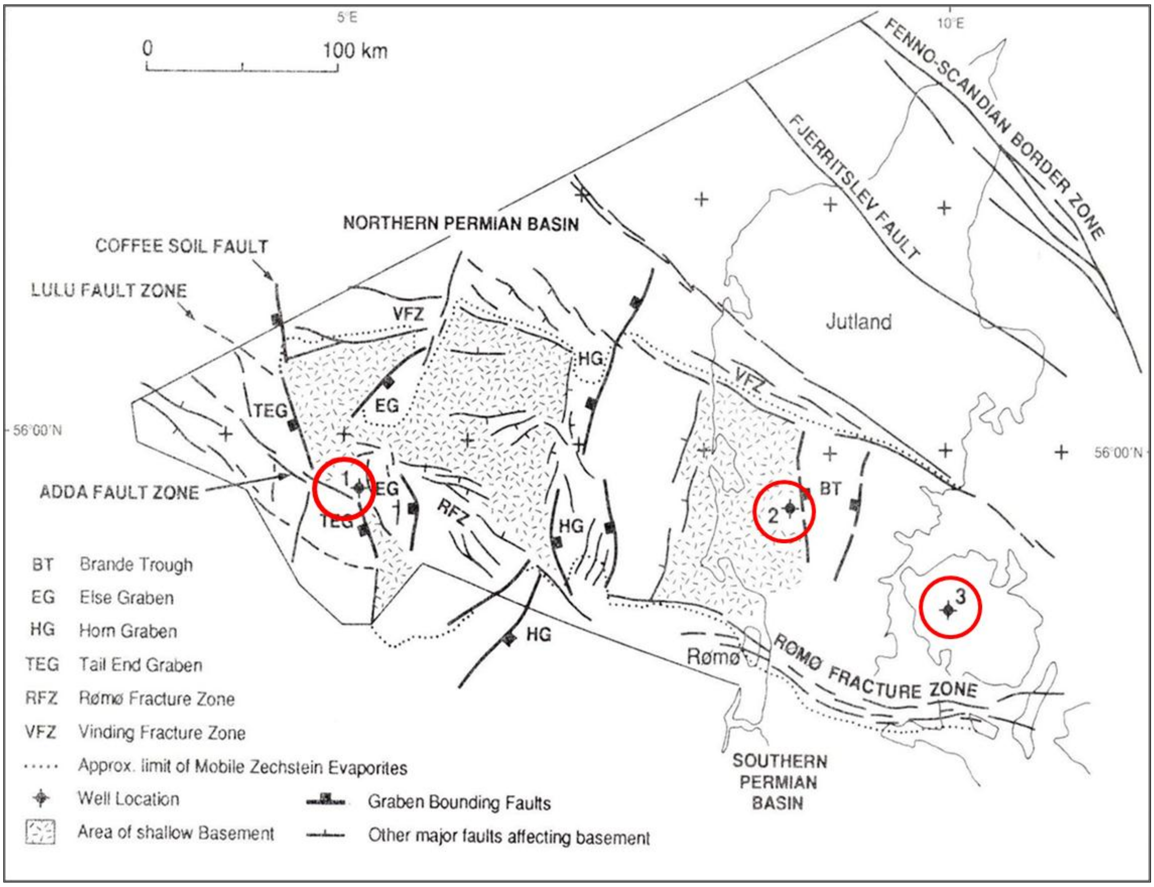


Figure. 2.7. Main Structural elements associated with the Ringkøbing-Fyn-High are shown in detail with wells (**1**-Per-1; **2-** Grinsted; **3**-Glamsbjerg) in red circles penetrating to crystalline basement (modified from Cartwright, 1990).

CHAPTER 3

DATA AND METHOD

3.1. Introduction

This chapter describes the basic methods used to interpret the structural evolution of the project area using the seismic, well and Bouguer gravity anomaly data sets. A general work flow used for this research is described in figure. 3.1.

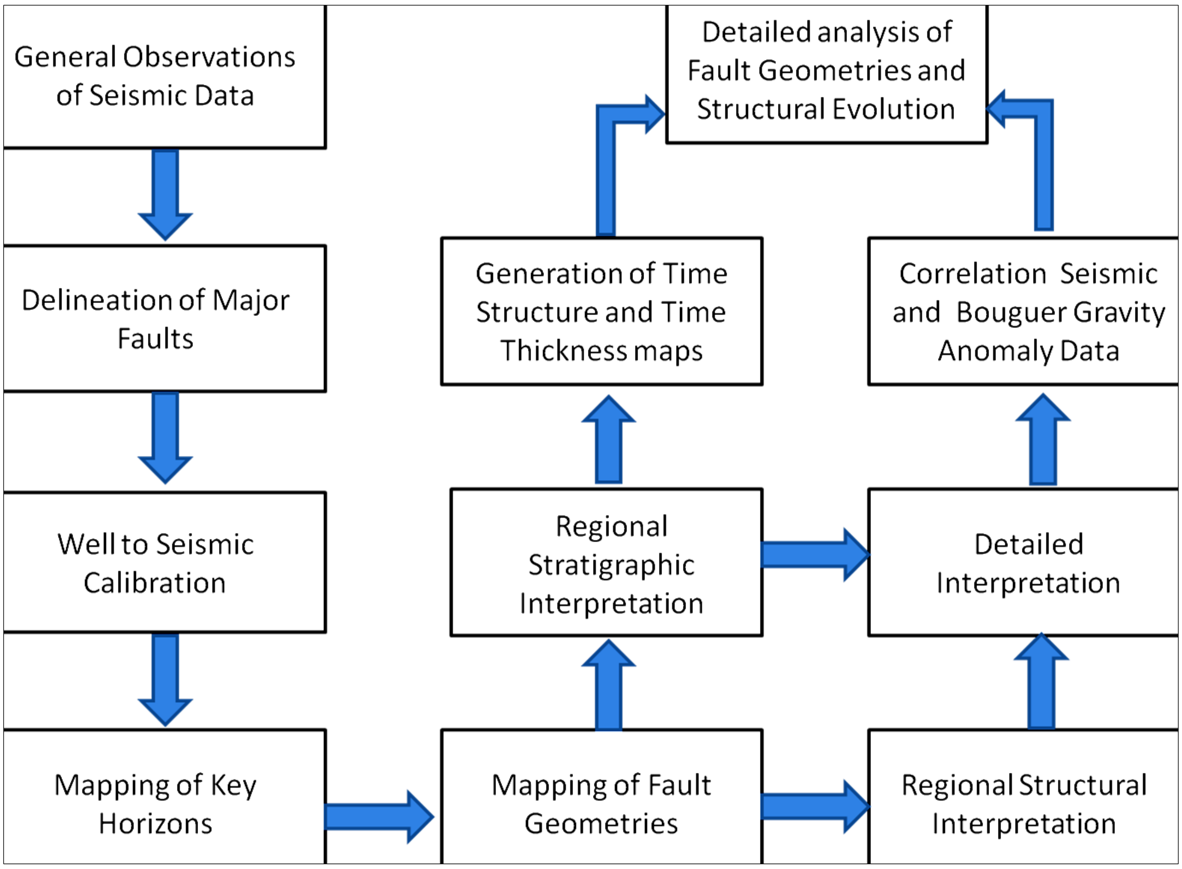


Figure. 3.1. Work flow showing a general strategy for interpreting the seismic and gravity data.

3.2. Available Data

Different types of data sets were used to perform this research study i.e. seismic data, well data and Bouguer gravity anomaly data.

3.2.1. Seismic data

A set of 2D seismic lines from six different surveys has been used for this study. The available seismic data cover many important structural elements such as parts of the Norwegian Danish Basin in the north, the Central Graben (CG) in the southwest, the Horn Graben (HG) in the southeast and the Ringkøbing-Fyn-High in between both grabens. A base map of the seismic surveys used for the present study is given in figure. 3.2.

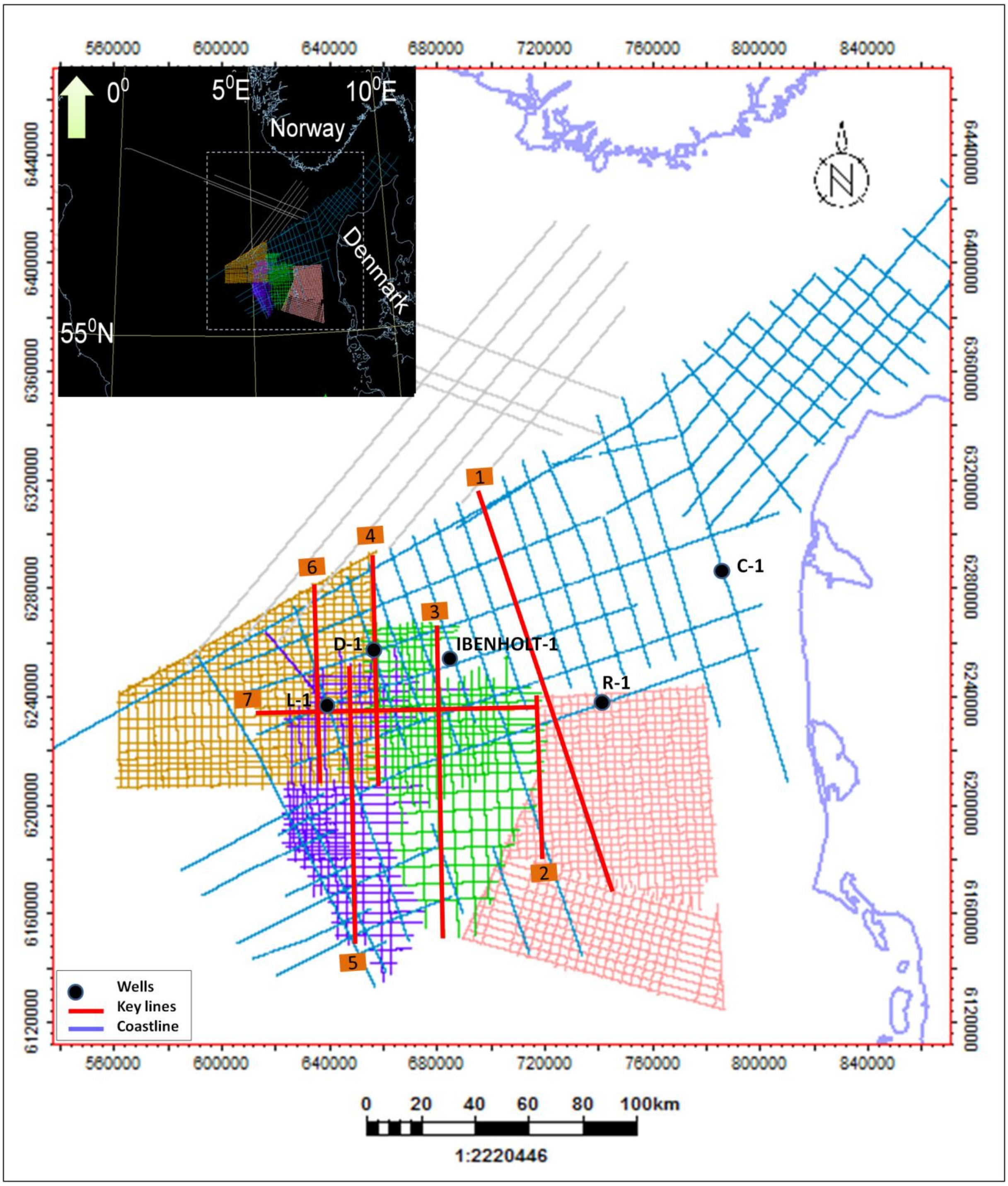


Figure. 3.2. 2D Seismic data set used for the seismic interpretation from six different surveys. A regional picture of the data set is explained in the top right corner. The location of the key seismic lines (numeric characters) and wells in the area is shown on the map.

3.2.2. Well data

Five wells were used in the seismic interpretation of the study area. Only one well (Ibenholt-1) is penetrating into the basement rocks in the study area, while the other 4 wells cut the lower volcanic unit of the Rotliegend Group (early Permian). The locations of the wells are shown in figure 3.2. Other information about the wells is given in tables 3.1 and 3.2.

Table. 3.1. Lithostratigraphic and general information of the wells is given below. The mapped horizons are given blue color (modified from www.geus.dk).

Well name	L-1X		D-1X		R-1X		C-1X		IBENHOLT-1	
Location	5° 14′ 55.2″ **E** 56° 15′ 9.7″ **N**		5° 31′ 52.2″ **E** 56°25′ 29.7″**N**		6° 53′ 45.6″ **E** 56°12′ 57.4″**N**		7° 40′ 0.0″ **E** 56°36′ 41.5″**N**		5° 58′ 28.7″ **E** 56° 23′ 25.6″ **N**	
Total depth drilled below msl (m)	2671		3528		2676		3169		2558	
Reference level (kelly bushing) above msl (m).	37.18		37.18		26.21		37.18		40.84	
Lithostratigraphy (depth below msl)	**Top (m)**	**Base (m)**	**Top (m)**	**Base (m)**	**Top (m)**	**Base (m)**	**Top (m)**	**Base (m)**	**Top (m)**	**Base (m)**
Post Chalk Group	55	2015	49	1205	37	891	27	575	39	1447
Chalk Group	2015	2316	1205	1462	891	1180	575	1130	1447	1641
L. Cretaceous units	2316	2377	1462	1511	1180	1262	1130	1286	1641	1701
Jurassic units	2377	2416	1511	1543	1262	1303	1286	1373	1701	1749
Triassic units	2416	2455	1543	1687	1303	1998	1373	2529	1749	1954
Zechstein Group	2455	2553	1687	2321	Missing		2529	3161	1945	2491
Rotliegende Group	2553	2671	3321	3528	1998	2676	3161	3171	2491	2533
Top Basement	Not penetrated		Not penetrated		Not penetrated		Not penetrated		2533	2558

Table. 3.2. TWT (ms) for the lithostratigraphic units of all the wells used for the seismic calibration. The horizons mapped during seismic interpretation are colored in blue (modified from Nielsen & Japsen, 1991).

Well Names	L-1X	D-1X	R-1X	C-1X	IBENHOLT-1
Lithostratigrahphic Groups	**TWT (ms) for encountered Horizons at the tops**				
Post Chalk Group	74	66	50	36	53
Chalk Group	1974	1239	958	605	1389
L. Cretaceous Group	2108	1355	1135	957	1478
Jurassic units	2147	1391	1202	1081	1520
Triassic units	2176	1416	1230	1151	1559
Zechstein Group	2201	1501	Missing	1863	1696
Rotliegende Group	2236	2252	1693	2138	1910
Top Basement	Not Penetrated	Not Penetrated	Not Penetrated	Not Penetrated	1931

3.2.3. Bouguer gravity anomaly data

Bouguer gravity anomaly data combined with seismic data is mainly used for the mapping of the top basement rocks (*fig. 3.3*). By comparing the seismic data with Bouguer gravity anomaly data, mapping of the basement rocks becomes more precise. The interpretation of the gravity data will be uncertain without subtracting the response of the near surface structures including shallow and large bodies which can produce high wavelength anomalies (Lyngsie et al., 2006). Ebbing and Olesen (2010) said that to some extent, gravity data are helpful in mapping the top basement and mostly the geological interpretation of the gravity data reveals a structural model which is geologically acceptable (Cordell and Henderson, 1968). A regional picture of the Bouguer gravity anomaly data (50 km High Pass Filtered) in the study area is shown in figure 3.3.

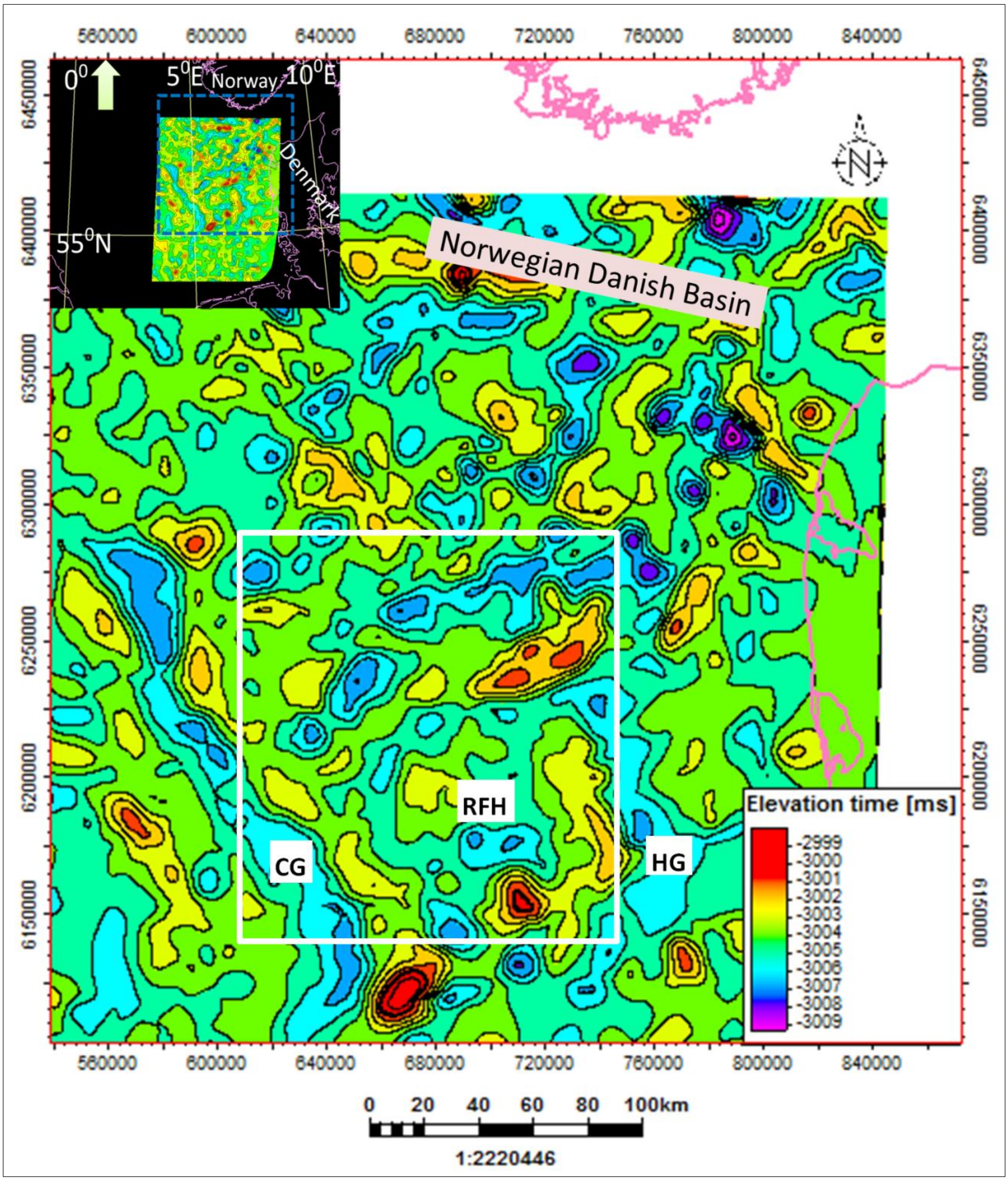


Figure. 3.3. 50 km High Pass Filtered Bouguer gravity anomaly data. The colors in this Bouguer gravity anomaly map show the variations in the gravity due to density differences in the Earth. The positive gravity anomalies (red color) show areas with higher densities and negative anomalies (purple color) show areas with lower values of density. The gravity data was adjusted to the seismic time values. The white square shows the location of the basement fault map (see *fig. 4.1 in chapter 4*). CG: Central Graben, HG: Horn Graben, RFH: Ringkøbing-Fyn High.

3.3. Interpretation Method

Before starting the seismic interpretation, a literature study was carried out to understand the general regional tectonic and structural history of the area. The software used for the interpretation is Petrel^{TM} (Schlumberger). In the beginning, a general overview of the data was completed and few regional lines covering the Ringkøbing-Fyn High (RFH) and part of the Norwegian Danish Basin (NDB) were selected to start the interpretation (*fig.3.2*). Primarily, major faults were mapped before going to the stratigraphic interpretation which lead to the general understanding of the regional geology. After mapping out the regional faults, well data were used for the calibration of the seismic horizons (*fig. 3.4 & 3.5*). At the start, well D-1 located on the northwestern border of the Ringkøbing-Fyn-High was used to calibrate the seismic horizons. The position of the well and details are shown in figure 3.2 and tables 3.1 & 3.2 respectively. Then, other wells were brought into use and key horizons were mapped all over the study area.

There was no well control on the Ringkøbing-Fyn-High itself and intense extensional faulting in the basement rocks made it difficult to map the sub-Chalk horizons. Regional mapping of the four key horizons was carried out in the whole project area which are:

- Top Chalk Group (late Cretacous)
- Base Chalk Group (mid Cretaceous)
- Top Zechstein Group (late Permian)
- Top Rotliegend Group (early-mid Permian)

Additionally, top Triassic and Jurassic units were mapped only on the key seismic lines due to study limits. It was also tried to map out the basement rocks and lower Rotliegend volcanics but because of limited quality of the seismic data, they are mapped only on few seismic sections.

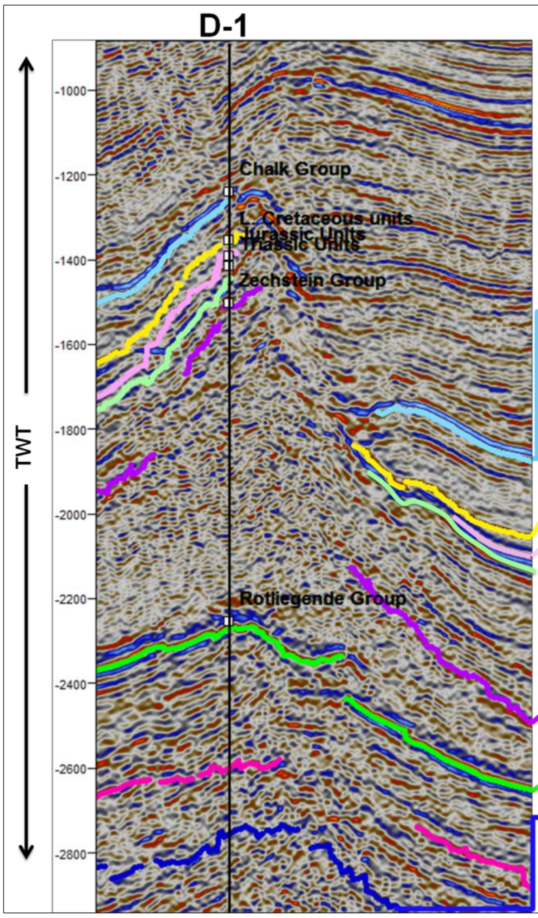
After mapping out the key seismic horizons, surfaces were produced which were used to create the time-structure maps (*fig. 4.9, 4.11, 4.13a & 4.14a*). Also, time-thickness maps of the Zechstein Group (late Permian) and Chalk Group (late Cretaceous) were generated (*fig. 4.12 & 4.15*). A detailed mapping of the fault geometries in the study area was carried out and fault maps at specific time intervals were drawn. Both software and manual techniques have been applied to create the fault maps.

To generate a fault map of a particular horizon, Petrel sketches all the faults cutting through the surface of that reflection. Due to nonexistence of the surface for the top basement, Petrel was unable to make a fault map at basement level. Then, manual procedure was adopted. All the seismic lines consisting faults in the study area were selected and their CDP's were displayed in the map window. The CDP value of each fault was drawn manually on the seismic lines in the map. Then, carefully marked points were joined to get the trends of the faults. Finally maps were digitized.

At the end, key seismic lines were selected covering major fault segments and most of the structural variations in the study area leading towards a detailed analysis of the hrizontal and vertical fault geometries. In the seismic sections, red color of the reflectors represents positive reflection coefficient (high amplitude) and blue reflectors show negative reflection coefficient (low amplitude) (*fig. 3.4 & 3.5*). The main focus of the seismic interpretation was to perform a detailed structural analysis and to find out why and when the Ringkøbing-Fyn-high was formed.

3.4. Seismic to Well Correlation

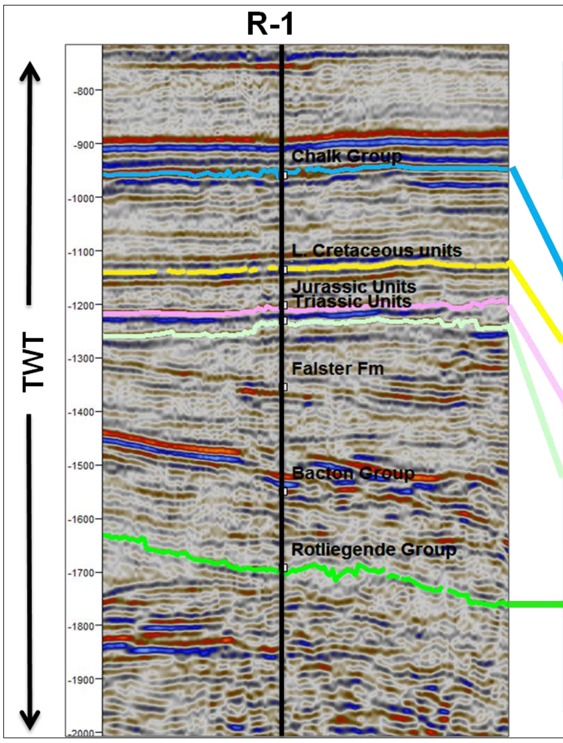
Due to complex geological structures in the study area, the accuracy of the seismic interpretation was more dependent on the well data. In order to get utmost quality of the work, data from five wells are used for the study validation. As figure 3.2 shows that all the accessible wells are drilled in the surrounding areas of the Ringkøbing-Fyn High. It is tried to extend the key horizons carefully towards the Ringkøbing-Fyn-High. A general procedure of seismic to well tie is shown below (*fig. 3.4 & 3.5*).



Depth below msl (m)	Tops of (Lithostrati-graphic Groups)	Age	Sub-Era
49	Post Chalk Group	Early Tertiary-Late Quaternary	Cenozoic
1205	Chalk Group	Late-Cretaceous	Mesozoic
1462	L. Cretaceous units	Early-Cretaceous	
1511	Jurassic units	Jurassic	
1543	Triassic units	Triassic	
1687	Zechstein Group	Late-Permian	Late-Palaeozoic
3321	Rotliegende Group	Early-Permian	
Not Penetrated	Top Basement	Pre-Permian	

Figure. 3.4. Seismic to well tei: Lithostratigraphic tops (in meters) of the well D-1X. TWT (ms) is shown on the vertical axis. Depths and ages of the groups are taken from www.geus.dk. The seismic line holding the well D-1 is given in figure 4.5.

The well D-1 is located in the area of NE-SW trending main boundary fault of the Permo-Carboniferous Else Graben on the northern border of the Ringkøbing-Fyn-High (Cartwright, 1990). This well is located on the salt diapir and well tops are disturbed because of upward movement of the salt. The cone shaped top Rotliegend Group (*fig. 3.4.*) below salt dome is due to less imaging control below salt deposits. The presence of the salt diapirs influence the quality of the imaging below the salt deposits. Salt produces a variety of complex noise which is sometimes impossible to remove during seismic processing. It is also a considerable obstacle to seismic penetration (pgs.com). The well R-1 is situated in the central part of the Horn Graben and 928 m thick succession of the sedimentary and volcanic rocks of Permian age has been penetrated (Nielsen & Japsen, 1991). The well data shows that the Zechstein Group of Permian age is missing here. The absence of the evaporites in the area of well R-1 is confirmed by seismic data which may infer that before and during the late Permian times, the northern segment of the Horn Graben was inactive (Vejbæk, 1990).



Depth below msl (m)	Tops of (Lithostratigraphic Groups)	Age	Sub-Era
37	Post Chalk Group	Early Tertiary-Late Quaternary	Cenozoic
891	Chalk Group	Late-Cretaceous	Mesozoic
1180	L. Cretaceous units	Early-Cretaceous	
1262	Jurassic units	Jurassic	
1303	Triassic units	Triassic	
Missing	Zechstein Group	Late-Permian	
1998	Rotliegende Group	Early-Permian	Late-Palaeozoic

Figure. 3.5. Seismic to well tei: Lithostratigraphic tops (in meters) of the well R-1X. TWT (ms) is shown on the vertical axis. The location of the well is shown in figure 3.2. Depths and ages of the groups are taken from www.geus.dk.

CHAPTER 4

SEISMIC INTERPRETATION

4.1. Introduction

In this chapter detailed stratigraphic and structural interpretation of the seismic key lines is addressed. Seven important key seismic lines were selected which cross cut the significant fault segments. It also explains how the combination of the seismic data and Bouguer gravity anomaly data support each other for more accurate interpretation of the basement rocks. The detailed analysis of the fault geometries gives an overview of the structural history at different time intervals which leads to understand the geological evolution of the study area.

The positions of the key horizons were correlated with well data. But, at places in the study area the horizons were disturbed due to tectonic processes. Therefore, further mapping was done on the basis of few opinions. A brief description of the judgments is given below on the basis of which key horizons (important for the study) are interpreted in the areas without well control.

4.1.1. Top basement

Identification of the top basement rocks on the seismic lines is done on the basis of personal observations and the views from different authors such as Scheck et al (2002). In the southern North Sea a strong double reflection is the general conduct of the basement rocks (Scheck et al., 2002). The trends of the Bouguer gravity anomaly data curves also helped cosiderably in the recognition of the top basement. One main trouble in estimating the top basement in the study area is volcanic activity covering most of the areas and on few seismic lines where basement reflector is not able to be recognized, that area is located more or less around the Caledonian Deformation Front (Reynisson et al., 2009; Reynisson, 2010; Ebbing and Olesen, 2010).

4.1.2. Top Rotliegend Group (Auk Formatoin)

The upper Rotliegend Group mostly consists of sandstone and claystones (Glennie et al., 2003). The top Rotliegend group in the seismic sections (*fig. 3.4 & 3.5*) has characteristics of positive reflection coefficient. The overlying salt has less density as compared to underlying sandstone which gives a positive accoustic impedance contrast resulting in positive reflection coefficient. But, top Rotliegend behaves different in different wells, such as:

- Top Rotliegend is a very strong reflector with positive reflection coefficient in wells D-1, L1, and Ibenholt (*fig 3.4*) because sandstone of Rotliegend group is underlying Zechstein salt and this gives a large impedance contrast resulting in strong positive reflection coefficient.
- But, in well R-1 salt of Zechstein Group is missing and top Rotliegend Group is overlain by primarily Triassic sandstones. Because of less impedance contrast between

Rotliegend Group and Triassic units, the reflection representing the Top Rotliegend Group is not strong (*fig. 3.5*).

In the densely faulted areas of the Rinkøbing-Fyn High, top Rotliegend Group was mapped keeping two things in mind:

i. Strong amplitude
ii. Trends from the surrounding areas

4.1.3. Top Rotliegend volcanics

It is very difficult to distinguish the volcanics from basement rocks on the seismic data (as mentioned above, see 4.1.1). But on few seismic sections, mapping of the volcanics is done on the basis of strong amplitude as compared to the overlying clastic strata and underlying basement rocks. Though, it is important to consider that Rotliegend volcanics are not present everywhere.

4.2. Description of the Fault Geometries and Architecture of the Ringkøbing-Fyn High

The Ringkøbing Fyn High is cut by the north-south trending Horn Graben and is subdivided into a western and an eastern part (*fig. 2.7*). The western part of the Rinkøbing-Fyn High is bounded by the Central Graben in the west and Horn Graben in the East. The study area is divided into different fault segments (A, B, C, D, E) on the basis of dip and strike trends of the fault sets (*fig. 4.1*) and two more structural elements including Tail End Graben (TEG) and Else Graben (EG) as mentioned by Cartwright (1990) .

Two major WNW-ESE trending fault complexes, the Rømo Fracture Zone (RFZ) in the south and the Vinding Fracture Zone (VFZ) (*fig 2.7*) in the north, differentiate the Ringkøbing-Fyn High from the the surrounding basins. In the east, towards Jutland the Vinding Fracture Zone is a 10-15 km wide zone of concentrated faulting from offshore to west of Jutland. In the south of Jutland, the Ringkøbing-Fyn High is described as a structural entity linked to the WNW-trending magnetic anomaly (Cartwright, 1990). In the study area, segment C in the southern fraction can be correlated with fault zone Rømo Fracture Zone mentioned by Cartwright (1990). In the same way fault segment E in the north of the study area can be correlated to the Vinding Fracture Zone (*fig. 4.1*).

The fault map of the basement rocks is used as a reference for the description of the fault segments (*fig. 4.1*). It has significant role in understanding the configuration of the Ringkøbing-Fyn-High. The whole study area comprises of gentle to steep dipping planar and listric normal faults. Fault-dips are apparent mentioned in the text below. Local fault segments in the study area are:

1) Segment A (A1, A2, A3 & A4) in the central part has a NE-SW strike direction (e.g. A1 & A2) in the northern part and towards south trend turns into E-W direction (e.g. A3 & A4). The dip of the normal faults is more than 55ºS or SE (*fig. 4.1*).

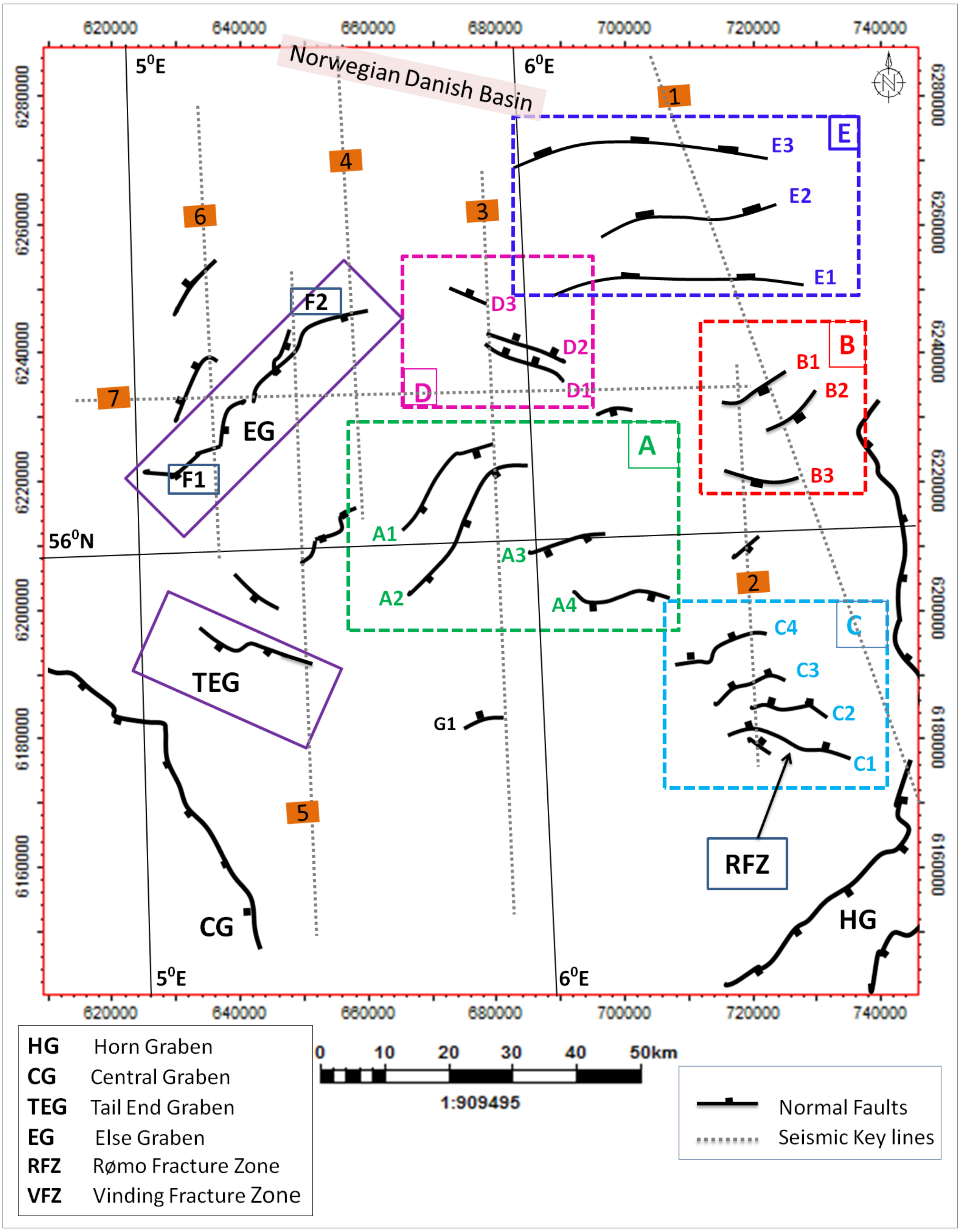


Figure. 4.1. Fault map of the top Basement rocks in the study area. Fault segments are shown in the colored rectangles on the map. RFZ, VFZ, TEG and EG for the grabens and fault zones are taken from Cartwright (1990). Seismic key profiles are shown in map as well represented by numeric characters 1-7 in the orange colored boxes. Location of the fault map is shown in chapter 3 (*fig. 3.3*, white square).

2) Segment B (B1, B2 & B3) in the central eastern most part shows a strike of NE-SW direction (e.g. B1 & B2) in the north and towards the south the strike of the faults becomes E-W (e.g. B3). Dip angle for the normal faults is more than 50º SE & S (*fig. 4.1*).
3) Segment C (C1, C2, C3 & C4) in the southeastern corner exhibit ENE-WSW (e.g. C4 & C3) to nearly ESE-WNW (e.g. C1 & C2) strike trend of normal faults. A general northward dip slip component is slightly steeper than segment B to the north.

   The faults in segments B and C dip in the opposite direction but towards each other. The original throw along the normal faults of the segments B and C is not measureable because of erosion on the crests of half-grabens. A dome shape of the basement rocks in the central part between segments A, B and C is observed.

4) Segment D (D1, D2 & D3) is close to the northern boundary of the Ringkøbing-Fyn High and occupies a strike of ESE-WNW direction. These nearly vertical normal faults are dipping towards north and mark the northern boundary of the Ringkøbing Fyn High. The Zechstein salt and Tertiary sequences are pinching out above these faults.
5) Segment E in the northern part of the study area is characterized by normal faults E1, E2 and E3. The strike of the faults is nearly E-W having a dip direction towards north.
6) The Else Graben sonsists of two segments having bi-polar structure (*fig 2.7 & 4.1*). The segments occupy basement faults with opposite dips showing half-graben geometries (Cartwright, 1990). In the study area, the northern segment of the Else Graben with NE-SW strike trend is mapped which is dipping towards southeast. This segment is further subdivided into two parts:
   a. The Northern part of the northern segment is represented by F2 (*fig. 4.1 & 4.10*).
   b. The Southern part of the northern segment showed by F1 (*fig. 4.1 & 4.10*).
7) The Tail End Graben is situated in the southwestern part of the Ringkøbing Fyn High and shows a half-graben geometry.

A few minor faults also occur in the study area but currently no thrust faults have been observed in the late Palaeozoic and younger strata. Though, basement rocks have been subjected to compressional tectonics during Caledonian Orogeny (Abramovitz and Thybo, 2000) but these deep structures are excluded from this study.

Each fault segment is assigned a color code to differentiate them easily. These color codes are given below:

- **Segment A**
- **Segment B**
- **Segment C**
- **Segment D**
- **Segment E**

4.3. Description of the Key Seismic Lines

There were plenty of seismic lines covering the study area but it was important to enclose the most important structural features and fault geometries on the basis of which key seismic lines are selected for the detailed structural interpretation. The locations of the selected key lines are shown in figure 3.2.

Few important considerations regarding description of the seismic interpretation are:

1. The color codes and names for the fault geometries on the seismic sections are the same as for the fault segments on the fault maps (*fig. 4.1 &4.10)*.
2. Most of the times, the seismic horizons are mentioned with their names in the description of the key lines. Their ages are given in figures 3.4 and 3.5.
3. The key seismic lines do not always cross cut all the fault segments mentioned in figures 4.1 & 4.10.
4. The observed unconformities are named in chronological ascending order from older to younger time gaps.
   a) Unconformity-1: Represents hiatus from early-mid Permian to late Triassic (*fig. 4.2*).
   b) Unconformity-2: Represents hiatus from mid-Permian to early Jurassic succession (*fig. 4.8*).
   c) Unconformity-3: Represents hiatus from late Permian to early Cretaceous (*fig. 4.4 & 4.7*)
5. Names for the horsts separating the northern boundary of the Ringkøbing-Fyn High are given in ascending order from east to west.
   a) Horst (H1), between fault segments B & E (*fig. 4.2 & 4.3*)
   b) Horst (H2), between fault segments A & D (*fig. 4.4)*
   c) Horst (H3), between Else Graben (EG) and Tail End Graben (TEG) (*fig. 4.6*)

4.3.1. Key Line 1

This regional seismic line has a NNW-SSE strike and is located in the northeastern part of the project area which is covering both the Norwegian-Danish Basin and the Ringkøbing-Fyn High. This seismic line covers fault segments B having strike ENE-WSW direction, segment C having strike direction of E-W to ESE-WNW and Vinding Fracture Zone (VFZ) which marks the northern boundary of the Ringkøbing-Fyn High (*fig. 4.2*).

The fault segment C on the seismic key line 1 is not mapped on the basement fault map due to change in direction of the seismic lines at that point but they must be the part of the segment C shown in figure 4.1.

In this regional key seismic line top Basement, top Rotliegend Group, top Zechstein Group, top Jurassic units, base Chalk Group and top Chalk Group are mapped. It is clear that the basement rocks are shallower up to 2.5s TWT under Ringkøbing-Fyn High as compared to below Norwegian-Danish Basin in the seismic section. The thickness of the sedimentary units decreases from the Norwegian-Danish Basin to Ringkøbing-Fyn High. Most of the Rotliegend Group deposition took place in wedge shape settings and it is thicker in the half-grabens as compared to above horsts on the Ringkøbing-Fyn High. The lower boundary of the Rotliegend group is not clear due to lack of well data but upper Palaeozoic sedimentary rocks have been interpreted with the help of seismic data in the half-grabens below Rotliegend Group (discussed in CH 5). Late Permian Zechstein salt and Triassic units are onlapping the Rotliegend Group on the northern flank of the Ringkøbing-Fyn High (*fig. 4.2 & 4.2A*). The Triassic Units are thick up to 2550 ms (twt) in the Norwegian-Danish Basin and have been strongly affected by salt intrusions but over the Ringkøbing-Fyn High they are only present in the half-grabens of the fault segment B. Triassic succession is not present on the Ringkøbing-Fyn High. A thin succession of the Jurassic units is present all over the region. The thickness of the upper Cretaceous Chalk Group is also less on the Ringkøbing-Fyn High as compared to the Norwegian-Danish Basin.

Additionally, an unconformity is identified on the seismic section named as Unconformity-1. Early-mid Permian to late Triassic succession is absent on the horst (H1) and on the central part of the Ringkøbing-Fyn High (*fig. 4.2 & 4.2 A*). This time gap in deposition is named as Unconformity-1. The age of the thin succession between top basement and top Triassic on the horst H1 is unknown.

The seismic section explains few major structural elements which include:

i. Ringkøbing-Fyn High (RFH) in the south
ii. Norwegian-Danish basin (NDB) in the north
iii. A horst (H1) separating the RFH and NDB

The Ringkøbing-Fyn High is bounded by a horst (H1) in the north and fault segment C in the south. The faults in the segment C show a planar to slightly listric fault geometry cutting basement rocks downward (*fig. 4.2*). C1 and C2 cut early to mid-Permian Rotliegend Group upward while C4 is cutting base Chalk Group of the late Cretaceous age and C3 incises top late Cretaceous succession. Fault segment C consists of rather small rotated half-grabens and all the faults generally dip apparently towards north.

The faults (B1, B2, B2a, B3 & B4) of the segment B also display planar to slightly listric fault geometries but here vertical displacement along the faults at basement level is more than segment C. These faults are cutting basement rocks downward and Triassic units upward. At basement level, the stratigraphic throw along the major fault B1 is measured up to 1850 ms (twt). The faults B1, B2 and B3 are same as shown on the basement fault map (*fig. 4.1*).

The horst (H1) is located on the northern margin of the Ringkøbing-Fyn High which separates it from the Norwegian-Danish Basin. It is bounded by fault segments E in the north and B in the south. The tectonic position of the horst (H1) supports that it must be considered as a part of the Ringkøbing-Fyn High.

Segment E (E1, E2, E3, E4 & E4a) is corresponding to the Vinding Fracture Zone mentioned by Cartwright (1990). It exhibits planar fault geometry with apparent northward dip slip component (*fig. 4.2*). The current vertical displacement at basement level along the main fault E1 is 1500 ms (twt). As described by Cartwright (1990) that Vinding Fracture Zone in the north differentiate the Ringkøbing-Fyn High from the the Norwegian-Danish Basin (*fig. 2.7*) and towards Jutland area it is a 10-15 km wide zone of concentrated faulting from offshore to west of Jutland. But, in this seismic section it covers more than 15 km of lateral width. All the faults in the segment E are synthetic to main fault E1 except falut E4a which displays antithetic geometry.

Northern structural element, the Norwegian Danish Basin is characterized by thick package of Mesozoic and Cenozoic succession. The intensity of the salt diapirs increases towards north in the Norwegian-Danish Basin. Few younger normal faults have generated above the salt diapirs making a graben structure.

At the end, precision of the basement faults was confirmed through comparison with Bouguer gravity anomaly data which matches best to the interpretation.

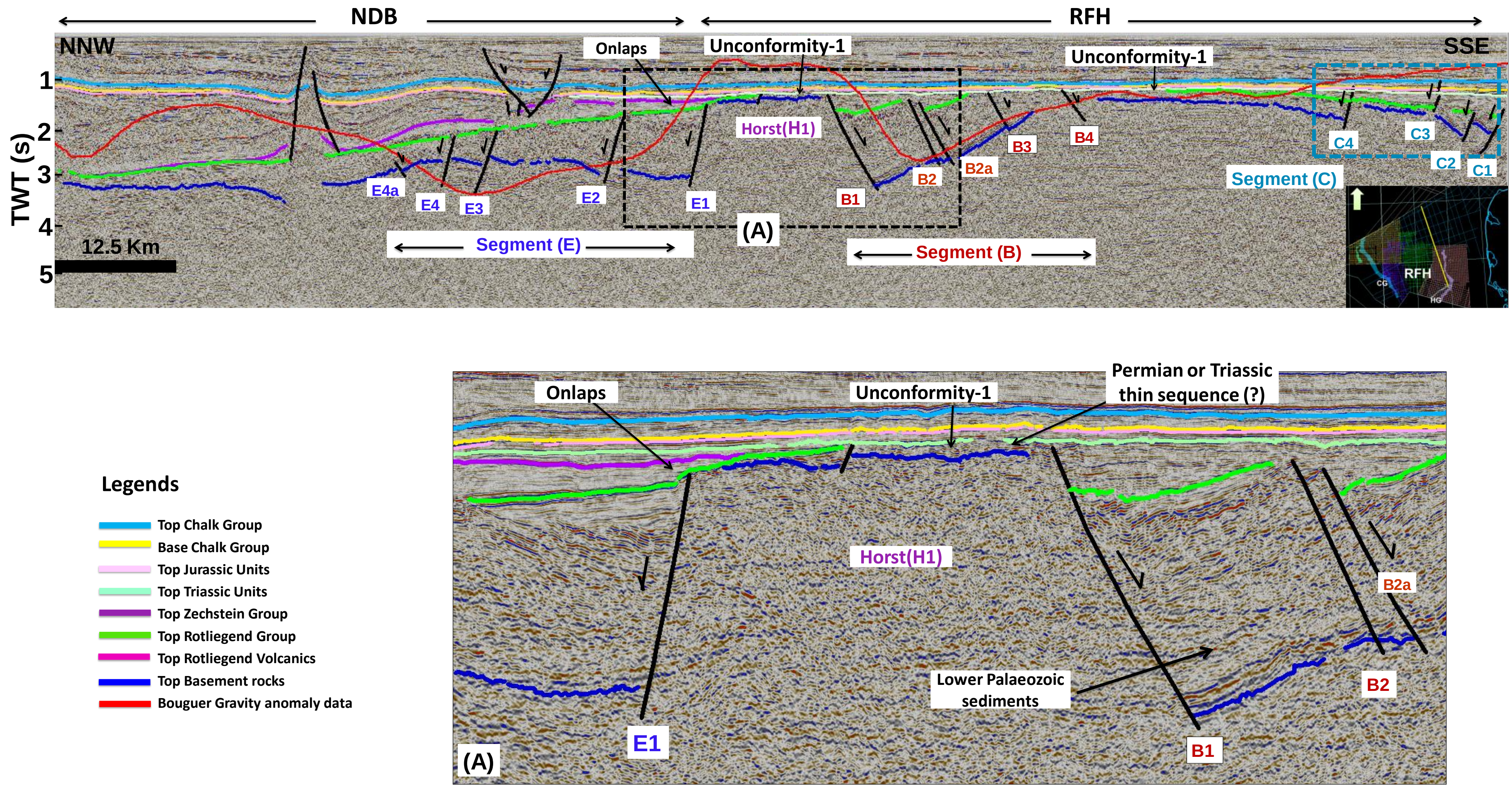


Figure. 4.2. Seismic interpretation of a regional key line 1. The location of the seismic line is shown in the lower right corner of the section and in figure 3.2. The zoomed-in box (A) is explained in detail. Color codes for the mapped horizons are shown in left bottom corner. RHF: Ringkøbing-Fyn High, NDB: Norwegian-Danish Basin.

4.3.2. Key Line 2

This north-south trending seismic line is located on the eastern part of the Ringkøbing-Fyn-High. It cross cuts two main fault segments, B in the north and C in the south (*fig. 4.3*). This seismic line is bounded by interesting fault geometries.

Basement rocks are shallower in the middle part of the seismic section as compared to the surrounding half-grabens. They are characterized with intense normal faulting. The sedimentary succession below Rotliegend Group parallel to the basement reflection in the half-grabens has been interpreted as older than Rotliegend Group. Their age is discussed in chapter 5. These reflections are strongly influenced by probable multiples between faults B2a and B2b (*fig. 4.3A*). Early-mid Permian Rotliegend Group shows different behavior to the rifting episodes in the north and south. Top Rotliegend Group is more stable towards south and faulted in the north. The base of the Group is difficult to be distinguished. Most of the deposition of Rotliegend Group took place in the half-grabens. The sharp red reflector between top Rotliegend and top Basement represents the top volcanics of the lower Rotliegend Group. Age of the sequence between top Basement and base Rotliegend Group is unknown. Late Permian Zechstein Group is missing over the Ringkøbing-Fyn-High and a thin succession of the upper Triassic units is overlying the Rotliegend Group. Overall the whole sedimentary succession up to late Cretaceous above the central part of the Ringkøbing-Fyn-High is thinner than adjacent areas.

The missing succession of late Permian to late Triassic age is represented by Unconformity-1 (*fig. 4.3 & 4.3A*). The Rotliegend Group is also missing on the crests of the rotated fault blocks. The fault block between faults B3 and B3a consists of horizontal reflections probable multiples which are difficult to define here.

The segment B is characterized by listric normal faults B1 and B3. Fault B2 mapped on the map (*fig. 4.1*) is missing here. In this seismic line listric behavior of fault B1 & B3 is more obvious than in the seismic key line 1. It is observed that fault block is rotated more along B1 than B3 and vertical displacement at basement level is much higher along B1 than B3. Both faults cut basement rocks downward and lower Triassic units upward. Fault B4 is nearly vertical normal fault. It cuts basement rocks downward and Rotliegend Group (?) upward.

The fault segment C comprising faults (C1, C2, C3 and C4) displaying planar to slightly listric fault geometry is also explained in the description of the key line 1. Fault planes and sedimentary succession in the half-grabens of the segment C are dipping steeply than segment B. Segment C is penetrating to basement rocks downwards. However, upward incursion is different for all faults. Towards up, C1 incise base of the late Cretaceous, C2 and C4 cut intra early-mid Permian succession and C4 cuts mid-late Permian sequence.

A small number of new faults are visible in the seismic section. B3a and B3b are antithetic to the major faults B1 and B2. Fault 4Ca is antithetic to C4. The dip slip component along B3a and B3b is towards north and 4Ca dips in the south direction. C1a and C1b show synthetic geometry to the major fault C1. The horst (H1) in the north of the fault segment B (*fig. 4.3*) delineates the northern boundary of the Ringkøbing-Fyn High.

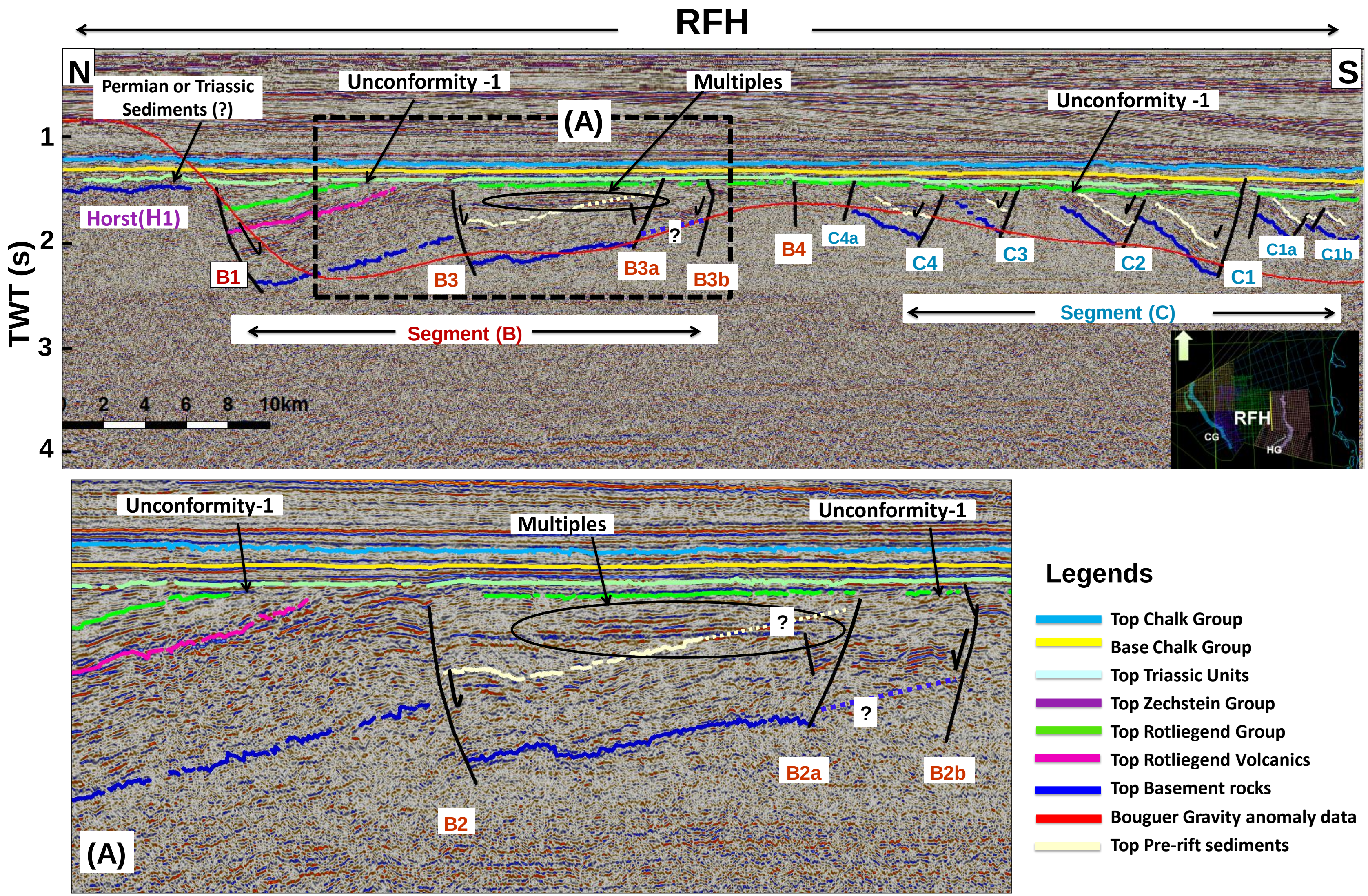


Figure. 4.3. Seismic interpretation of the seismic key line 2. Fault segments B and C are transected. The marked rectangle (A) Represents Unconformity-1 explained in the text. Color codes for the mapped horizons are shown in the right bottom corner. The location of the line is shown above and in figure 3.2. RHF: Ringkøbing-Fyn High, CG: Central Graben, HG: Horn Graben.

4.3.3. Key Line 3

This north south trending line is located in the central part of the Ringkøbing-Fyn-High which covers parts of the Norwegian-Danish Basin in the north. It transects fault segment D and part of the Segment A in the north. The seismic line is positioned in the vicinity of western border of the Ringkøbing-Fyn High. Here, configuration of the basement rocks is slightly different than eastern surrounding area.

It is observed that in the middle part of the Ringkøbing-Fyn High from fault A2 to G1 (*fig. 4.4*), top of the basement rocks displays dome shape as noticed in the seismic key line 2 (*fig. 4.3*). The position of the basement also deepens towards the west in contrast to the east. The middle part of the high on this seismic section encompasses thick Palaeozoic strata without any clues regarding the upper stratigraphic contact between Palaeozoic succession and the Rotliegend Group.

The wedge shaped deposition of the early-mid Permian Rotliegend succession is seen in the seismic section analogous to adjacent areas. But, the lower contact of the sequence is difficult to be marked here as well. Volcanics of the lower Rotliegend group (pink horizon) are mapped at some places. Late Permian Zechstein Group, Triassic and Jurassic units onlap the early-mid Permian Rotliegend Group (*fig. 4.4 & 4.4a*). The thickness of the late Permian and the Triassic units increases towards the NDB.

Upper Permian to upper Jurassic strata is missing on the northern margin of the Ringkøbing-Fyn High positioned on horst H2. This Unconformity-3 is analogous to observed on the key line 6 (*fig. 4.7*).

The regional seismic section can be divided into three structural elements:

i. Ringkøbing-Fyn High (RFH) in the south
ii. Norwegian-Danish basin (NDB) in the north
iii. A horst (H2) separating the RFH and NDB

In the north, the Ringkøbing-Fyn High is bounded by horst H2 (similar to horst H1 between fault segments B and E shown in figure 4.2) while southern border is not demonstrating any pronounced fault geometry. Fault segment A is representing the southern boundary of the horst H2 and consists of a set of four faults out of which A1 and A2 are intersecting this seismic line. The intra Ringkøbing-Fyn High fault segment A consists of planar normal fault A1 in the north. A2 displays anti listric fault geometry dipping apparently towards south. Both faults penetrate into basement rocks downward and early-mid Permian Rotliegend Group upward. The southward dip slip component along A2 is greater than A1 at basement and lower Permian intervals (*fig. 4.4a*).

Towards south, frequency of the faults is minimized and only G1 nearly vertical planar normal fault is observed dipping towards north. It also cuts basement rocks downward but upward penetration is unexplained due to unknown age of the succession. Though, it can be said that it continues to upper Palaeozoic sequence upward (?). A smaller normal fault G1a in the southern margin is cutting top Rotliegend group upward and does not penetrate to deeper level.

Fault segment D defines the northern boundary of the Ringkøbing-Fyn High. As, similar to horst (H1) (*fig. 4.2*) further in the east, horst (H2) should also be considered as a part of the Ringkøbing-Fyn High on the basis of its structural configuration. Segment D is characterized by both steep dipping planar normal faults (e.g. D1a,D1 & D2) and gently dipping planar normal faults (e.g. D2 & D3). Each fault in the segment D cuts to the basement rocks downward and dips apparently northward. Upward penetration of D1a, D1 and D3 is unknown due to the unidentified age of the sequence. However, D2 cuts early-mid Permian Rotliegend Group upward. A smaller fault D2a synthetic to D2 is observed which dissects proposed Rotliegend volcanics (*fig. 4.4*). Overall normal faulting is restricted to basement rocks.

The Bouguer gravity anomaly data shows more or less best fit to the seismic interpretation of the basement rocks.

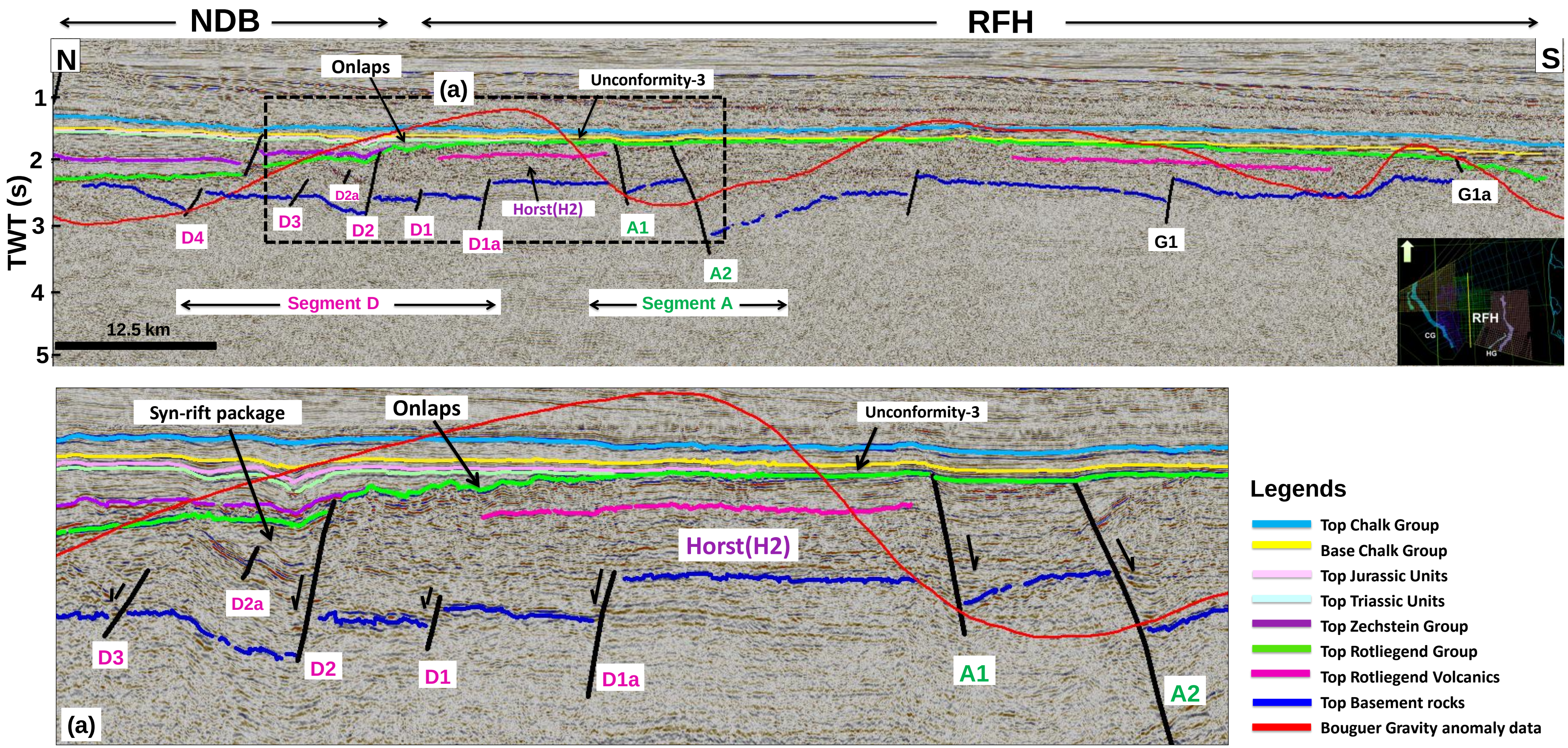


Figure. 4.4. Seismic interpretation of the rgional key line 3 through Norwegian Danish Basin (NDB) and Ringkøbing-Fyn High (RFH). The zomed-in box (A) shows an unconformity between top Rotliegend and lower Cretaceous succession. Color codes for the mapped horizons are shown in the right bottom corner. The location of the line shown in figures 4.4 and 3.2.

4.3.4. Key Line 4

This seismic line strikes N-S and resides in the northwest of the Ringkøbing-Fyn High. It is transecting the Else Graben in the south and part of the Norwegian Danish Basin in the north. The well D-1 (*described in fig. 3.4*) is located on this seismic line.

Densely spaced normal faulting in the basement rocks towards the Ringkøbing-Fyn High (*fig. 4.2, 4.3 & 4.4*) is not noticed here. Only depth to the basement rocks is increasing towards Norwegian Danish Basin. Permian Rotliegend Group shows more thickness in the Else Graben area while more or less constant thickness in the north towards Norwegian Danish Basin. Top Rotliegend Group shows a dome shape below salt diapirs due to velocity pull up effect.

Late Permian Zechstein salt has formed diapirs. The size of the salt diapirs is up to 1250 ms (twt). The Triassic succession is thickening towards the Norwegian Danish Basin. The Else Graben is positioned close to the northwestern border of the Ringkøbing-Fyn High and late Permian to early Cretaceous succession is onlapping the early-mid Permian Rotliegend Group (*fig. 4.5*).

The main fault F2 shows slightly listric fault geometry due to rotation of the fault block with apperent dip towards the south. The vertical dip-slip component at basement level is approximately 1000 ms (twt) and more than 300 ms (twt) at top Rotliegend Group interval. A small number of planar faults (F2a, F2b & F2c) synthetic to the main fault F2 are present. The dip angle of the fault F2c is analogous to main fault F2 but F2a and F2c have rather gentle dip angle.

F2a is cutting top Rotliegend Group upward and lower penetration of the fault is up to Palaeozoic succession of unknown age (discussed in Ch 5). Faults F2b and F2c cut basement rocks downward and towards up F2c cuts top Rotliegend Group.

Furthermore, Bouguer gravity anomaly data also makes a reasonable comparison with the top Basement rocks.

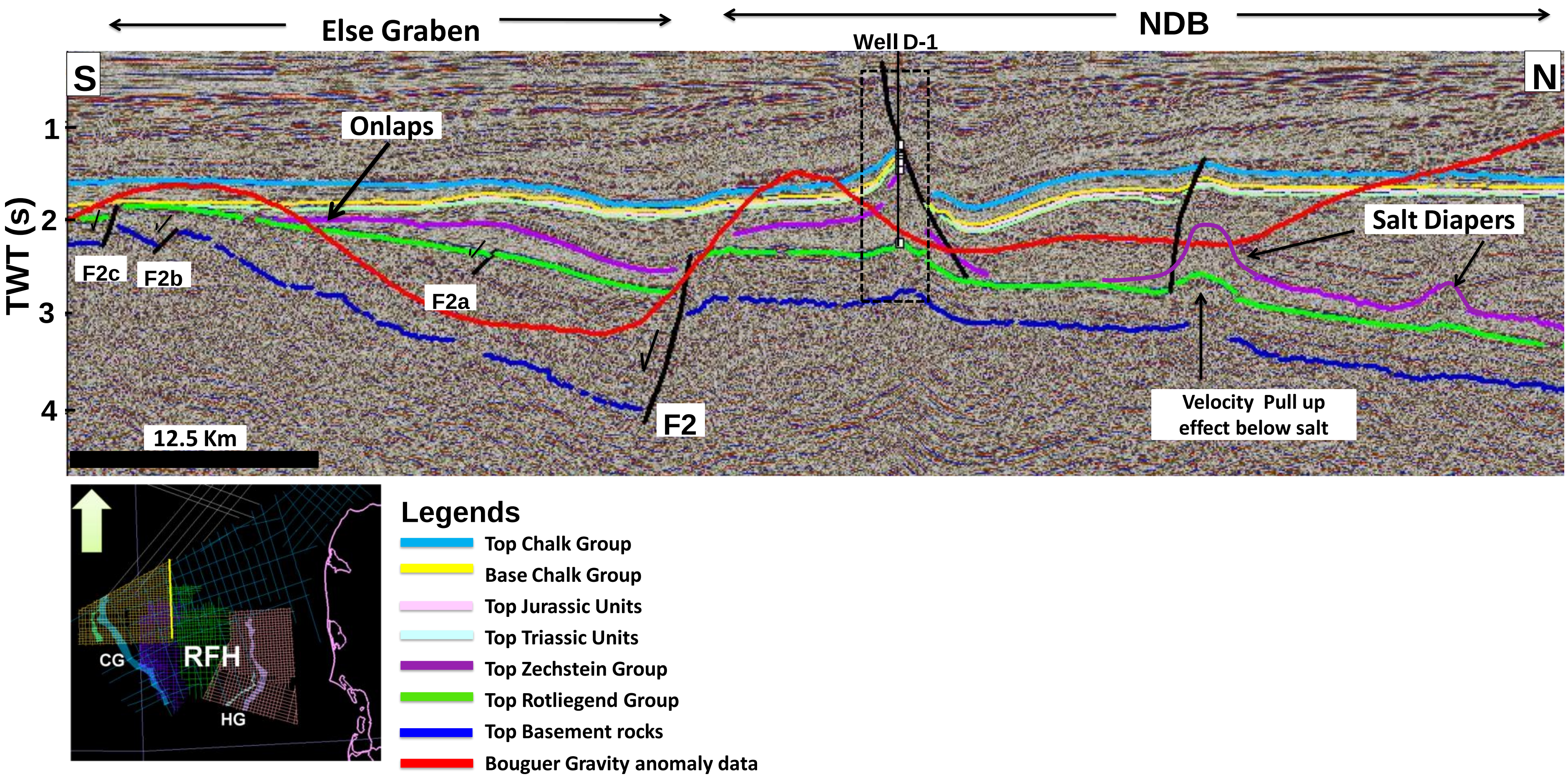


Figure. 4.5. Seismic interpretation of the key line 4 through Else Graben and Norwegian Danish Basin (NDB). The well D-1 is shown in figure 3.4. Color codes for the mapped horizons are shown in figure. The location of the line is shown in figures above and 3.2. RHF: Ringkøbing-Fyn High, CG: Central Graben, HG: Horn Graben.

4.3.5. Key Line 5

This north south trending seismic key line is located close to the western boundary of the Ringkøbing-Fyn High and cross cuts the Tail End Graben (TEG) in the south and Else Graben (EG) in the north (*fig. 4.6*).

Basement rocks are characterized by normal faults making a horst structure inbetween two grabens. The thickness and continuity of the reflections of the possible clastic succession are much greater in the Else Graben than in the Tail End Graben. Early-mid Permian Rotliegend Group is deposited in both half-grabens with variable thickness and underlies Permian Zechstein salt in the faulted blocks. The Zechstein salt pinching out towards the crests of the half-grabens. The southern most part of the seismic section is situated in the vicinity of the Central Graben (CG) and a salt dome at the edge of the section is visible making presence of thick salt layer clear towards south. Over the horst H3 late Triassic beds overly the thin Roliegend (?) beds which means mid Permian to early late Triassic succession is missing here. This is named as Unconformity-1 (*fig. 4.6 & 4.6B*). Thin Jurassic beds are encountered towards north and their presence in the south is not confirmed. Late Cretaceous Chalk Group shows continuous thickness over the whole area except erosional valleys similar to observed in figure 4.7.

Structurally seismic section is divided into three elements:

i. Else Graben (EG) in the north
ii. Tail End Graben (TEG) in the south
iii. Uplifted block horst (H3) in between

At northern and southern margins, the Else graben is bounded by main fault F2 (northern main fault of the southeastward dipping segment of the Else Graben) with listric fault geometry and a set (F2A) of faults antithetic to the main fault F2 respectively (*fig. 4.6*). At basement level vertical separation along F2 is 1200 ms (twt) (?). Another synthetic fault F2a exists in the north of the main fault F2. Apparent dip of faults F2 and F2a is southward. All the normal faults bounding Else Graben cut basement rocks downward. Upward penetration of the main fault F2 is upto early-mid Permian succession while later developed faut F2a is penetrating to late Permian Zechstein salt.

Tail End Graben is bounded by main fault T1 at northern margin which depicts a planar geometry cutting Rotliegend Group down to the basement rocks. Apperent dip direction of T1 is southward with vertical displacement of approximately 700 ms (twt) (?) at basement level while it becomes 600 ms (twt) (?) at top Rotliegend interval (*fig. 4.6*). Smaller faults T1a & T1c are synthetic to T1 and T1b, T1d & T1e display antithetic relationship to main fault T1. Majority of the smaller normal faults is focussed within the Rotliegend Group (*fig. 4.6*).

The horst (H3) between the two grabens is bounded by a northward dipping fault set F2A in the north and a southward dipping planar normal fault T1a in the south. Almost, all the faults cut succession from top Rotliegend to the Basement rocks downward. The area between

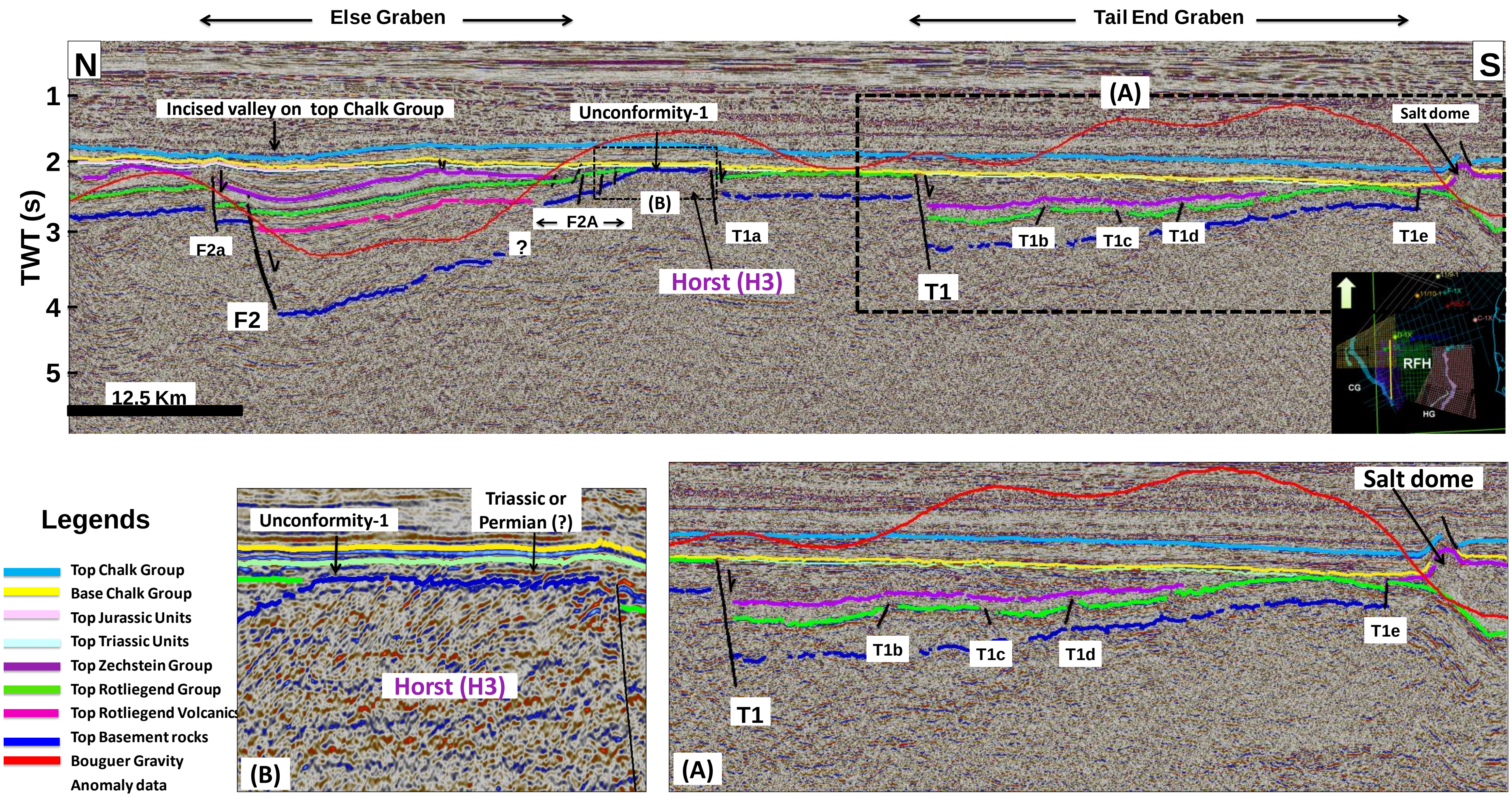


Figure. 4.6. Seismic interpretation of the key line 5 through Else Graben and Tail End Graben. The location of the line is shown in figures above and 3.2. RHF: Ringkøbing-Fyn High, CG: Central Graben, HG: Horn Graben.

T1 and T1a is showing an intermediate relief at basement level between Tail End Graben and horst (H3).

In the vicinity of the Ringkøbing-Fyn High, frequency of the faulting varies from bottom to top on the interpreted horizons. It is observed that the basement rocks are more disturbed by normal faulting and Rotliegend group is faulted intermediately with least faulting towards younger stratigraphic sequence (*fig. 4.6*).

The Bouguer gravity anomaly data shows best fit in the north while intermediate match to the south.

4.3.6. Key Line 6

This north-south trending seismic line is located in the south-western part of the Norwegian-Danish Basin and close to the northwestern boundary of the Ringkøbing-Fyn-High. It cross cuts the Else Graben located in the northwestern part of the study area.

The depth of the basement rocks in the study area is variable due to densely spaced normal faults at that level and display large half-grabens filled with probable Palaeozoic succession. But, the age of the sediments between Rotliegend Group and top Basement is unknown (discussed in chapter 5). Basement rocks display a dome shape in the area of Ringkøbing-Fyn-High between fault segment B and C.

Rotliegend Group occupies more thickness in the half-grabens as compared to above horst e.g. H3 between F3 and F1 (*fig. 4.7 and 4.7A*). Main Fault F1 is representing the northern boundary of the Else Graben and the lateral extension of the Graben ranges from 10 to 12 km on the seismic section. The Upper Permian Zechstein Group and Triassic succession pinch out on the northern flank of the horst (H3). The size of the salt diapirs and thickness of the Triassic succession increases towards the north in the Norwegian-Danish Basin. The Triassic sequence attains a thickness of up to 1000 ms (twt) in the seismic section. The most affected succession due to Salt intrusions are Triassic Units.

Over the horst bounded by faults F3 and F1 upper early-mid Cretaceous sedimentary beds are overlying the Permian Rotliegend Group which means upper Permian to lower Cretaceous succession is missing here which is shown by an Unconformity-3 (*fig. 4.7 & 4.7A*).

The younger mapped horizons include top and base of the upper Cretaceous Chalk Group which are less in thickness above the salt domes S1 and S2 than surrounding areas and above Ringkøbing-Fyn-High. Clausen and Huuse (1999) mapped the top Chalk Group surface in the offshore Denmark region and identified major erosional valleys on the top of it. Few erosional valleys are recognized in the study area as well. One of them is illustrated on the seismic section (*fig. 4.7*). Overall thickness of the sedimentary succession increases towards the Norwegian-Danish Basin.

The higher frequency of the normal faults and rotated blocks is restricted to basement rocks giving a very clear horst and graben structures. F1 is the master fault of the Else Graben showing listric fault geometry with apparent dip towards south. It cuts basement rocks downward and upper Permian Zechstein salt (?) upward. The vertical displacement along the fault F1 at basement and Rotliegend Group intervals is different. Due to probable erosion of the basement rocks on the horst H3, exact throw is unknown. At basement interval, the present vertical displacement along the fault F1 is up to 625 s (twt). The synthetic faults F1a and F1b show same geometry as master fault F1 (*fig. 4.7*). The normal faults F4 and F3 show planar fault geometry and cut basement rocks downward. Towards up, F3 cuts intra early-mid Permian Rotliegend group and F4 continues to lower Rotliegend volcanics (?) succession. At the top basement level the measured throw along F3 and F4 on the seismic section is 850 and 725 ms (twt) respectively (*fig. 4.7*). The apparent dip of the faults is more than 60° N. The frequency of the faults varies from older to younger successions. Normal faults are more concentrated in the basement rocks under Norwegian-Danish Basin and towards Ringkøbing-Fyn-High.

Two major faults J1 and J2 show planar to listric fault geometry and penetrate to upper Permian Zechstein salt downward and Tertiary to Quaternary succession upward. J1 displays a dip-slip component towards south and J2 shows a northward displacement. Few smaller faults J1c, J1b, J1a are antithetic to master fault J1. Another antithetic fault to the master fault J2 is cutting through Triassic to early Tertiary succession.

The Bouguer gravity anomaly data (red curve) was very useful to identify the top basement making the seismic interpretation more precise. The gravity data curves show best fit to the faults in the basement (*fig. 4.7*).

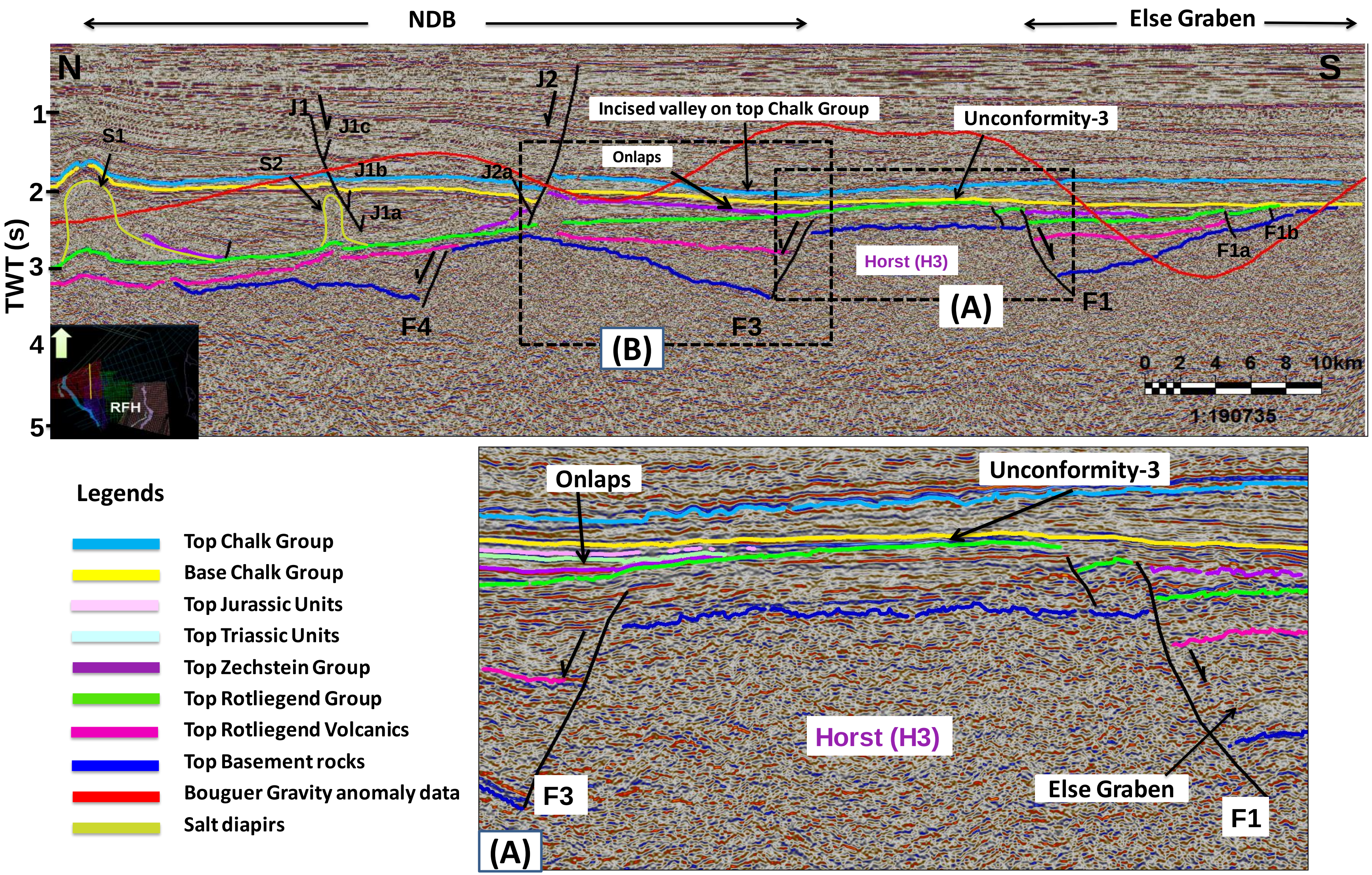


Figure. 4.7. Seismic interpretation of the key line 6 through Else Graben and part of Norwegian Danish Basin (NDB). The zoomed-in box (A) Represents an Unconformity-3 between Rotliegend and lower Cretaceous succession. **(B)** This zoomed-in part is explained in Chapter 5 (*fig. 5.4B)*. Color codes for the mapped horizons are shown in left bottom corner. The location of the seismic line is shown in figures 4.7 and 3.2.

4.3.7. Key Line 7

This east west oriented key seismic line is the combination of two seismic lines which belong to the northern boundary of the Ringkøbing-Fyn High. Towards west it cross cuts southern part of the northern segment of Else Graben (*fig. 4.1 & 4.8*) and horsts H2 and H1 to the east. Additionally, 5 north south trending seismic key lines represented by numeric characters also cross cut the seismic section (*fig. 4.8*).

In this seismic line mapped horizons include top Basement, Rotliegend Group, Zechstein Group (mainly salt), top Triassic, top Jurassic, top and base of the late Cretaceous Chalk Group. It is observed that top basement is positioned deeper and the thickness of the overlying clastic succession is increasing as we are moving to the north towards Norwegian-Danish Basin. Early-mid Permian Rotliegend Group reflections are dipping to the west in the Else Graben. Approximate maximum thickness of the clastic sediments from top Rotliegend Group to the basement rocks is upto 1400 ms (twt) in the Else Graben decreasing towards east. To the west of the Else Graben thickness of this succession decreases which could point out to the erosion of the sediments above the block. Lower contact of the Rotliegend Group is still a question needs to be solved but below the Rotliegend, lower Palaeozoic succession might have been deposited. Above the Rotliegend Group, Zechstein salt and the Triassic units are onlapping as described earlier (*fig. 4.2, 4.4 4.5, 4.7 & 4.8).* A general dipping trend of the sedimentary sequence is to the west.

A gap in the deposition from mid-Permian to early Jurassic age exists above horst H2 representing Unconformity-2.

The main features showed by the transect include:

i. Else Graben in the west (*fig. 4.1 & 4.7*)
ii. Horst (H1) between fault segment B and E (*fig. 4.1 & 4.2*)
iii. Horst (H2) between fault segment A & D (*fig. 4.1 & 4.4)*

The Else Graben is bounded by a major listric fault F1 in the west. It shows lower part of the northern segment of the graben mentioned by Cartwright (1990) (*fig. 4.1*). The apparent dip of the fault is towards east. A smaller fault F1a is synthetic to the main fault F1. F1b and F1c show antithetic relationship to the F1. These antithetic faults also show listric geometry. All faults cut basement rocks downward. F1, F1a & F1b go through the top Rotliegend Group towards up and F1c cuts slightly lower part of the Triassic strata.

Overall, the frequency of the faults is restricted to the basement rocks. Moreover, Bouguer gravity anomaly data confirms a good match to the mapping of the top basement rocks.

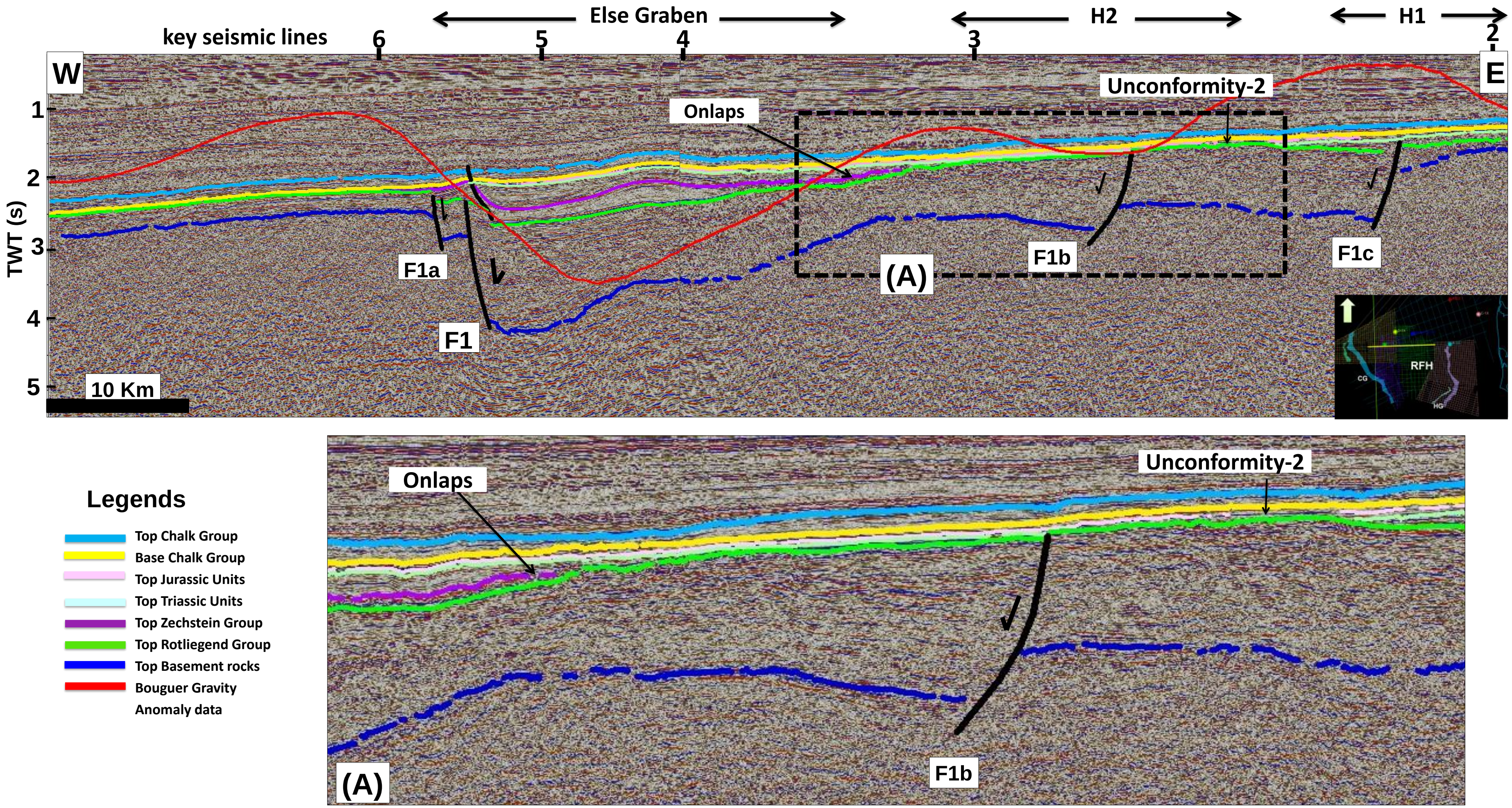


Figure. 4.8. Seismic interpretation of the rgional key lines 7 (which is combinition of two lines) through Else Graben and horsts H1 (shown in figure 4.2) and H2 (shown in figure 4.4). The zomed-in box (A) shows an unconformity-2 between top Rotliegend Group and lower Jurassic succession discussed in the text. Color codes for the mapped horizons are shown in the left bottom corner. The location of the line is shown in figure above and 3.2.

4.4. Time-Structure, Time-Thickness (twt) and Fault Maps.

In this section time-structure maps combined with fault maps have been used to see the lateral size and orientation of the structural elements. Time-thickness maps disclose the thickness variations of the strata helping the further study. The combination of the maps gives a comprehensive view of the major features in the study area. Furthermore, relationship of the structural entities with each other becomes more clear. Basement fault map has already been explained to show the major fault segments of the study area (*fig. 4.1*).

The horizons for which maps have been established are given below.

Time-structure maps of:

i. Top Rotliegend Group (early-mid Permian)
ii. Top Zechstein Group (late Permian)
iii. Base Chalk Group (late Cretaceous)
iv. Top Chalk Group (late Cretaceous)

Fault maps of:

i. Top basement rocks
ii. Top Rotliegend Group (early-mid Permian)
iii. Base Chalk Group (late Cretaceous)
iv. Top Chalk Group (late Cretaceous)

Time-thickness maps of:

i. Zechstein Group (late Permian)
ii. Chalk Group (late Cretaceous)

4.4.1. Rotiegend Group (early-mid Permian)

The early-mid Permian Rotliegend Group is mapped mainly on the Ringkøbing-Fyn High (RFH) and adjacent areas which include parts of the Central Graben (CG), Horn Graben (HG) and Norwegian-Danish Basin (NDB). The time-structure map nicely displays the major structural variations at the specific time interval. It shows a gradual deepening towards north to the Norwegian-Danish Basin and a sudden increase in the depth to the east and west. The greater depths in the area clearly separate the structural features from Ringkøbing-Fyn High (*fig. 4.9*). The color variations show that the norhern edge of the Norwegian-Danish Basin and central part of the Ringkøbing-Fyn High are relatively shallower parts in the region. The innermost fraction of the Norwegian-Danish Basin is much deeper than the surroundings.

The eastward dipping segment of the Horn Graben is much deeper in the south than northern part. The most deepest part observed is in the Central Graben to the west. Due to large contour interval smaller half-grabens are not displayed very well in the map. However, the Else Graben can be seen clearly on the map (fig. 4.9). The vertical displacement in the central part of the graben is more than edges.

It is very important to consider that over the Ringkøbing-Fyn High, the succession is eroded at places but due to software complication, it is not possible to exclude the areas of erosion from the map.

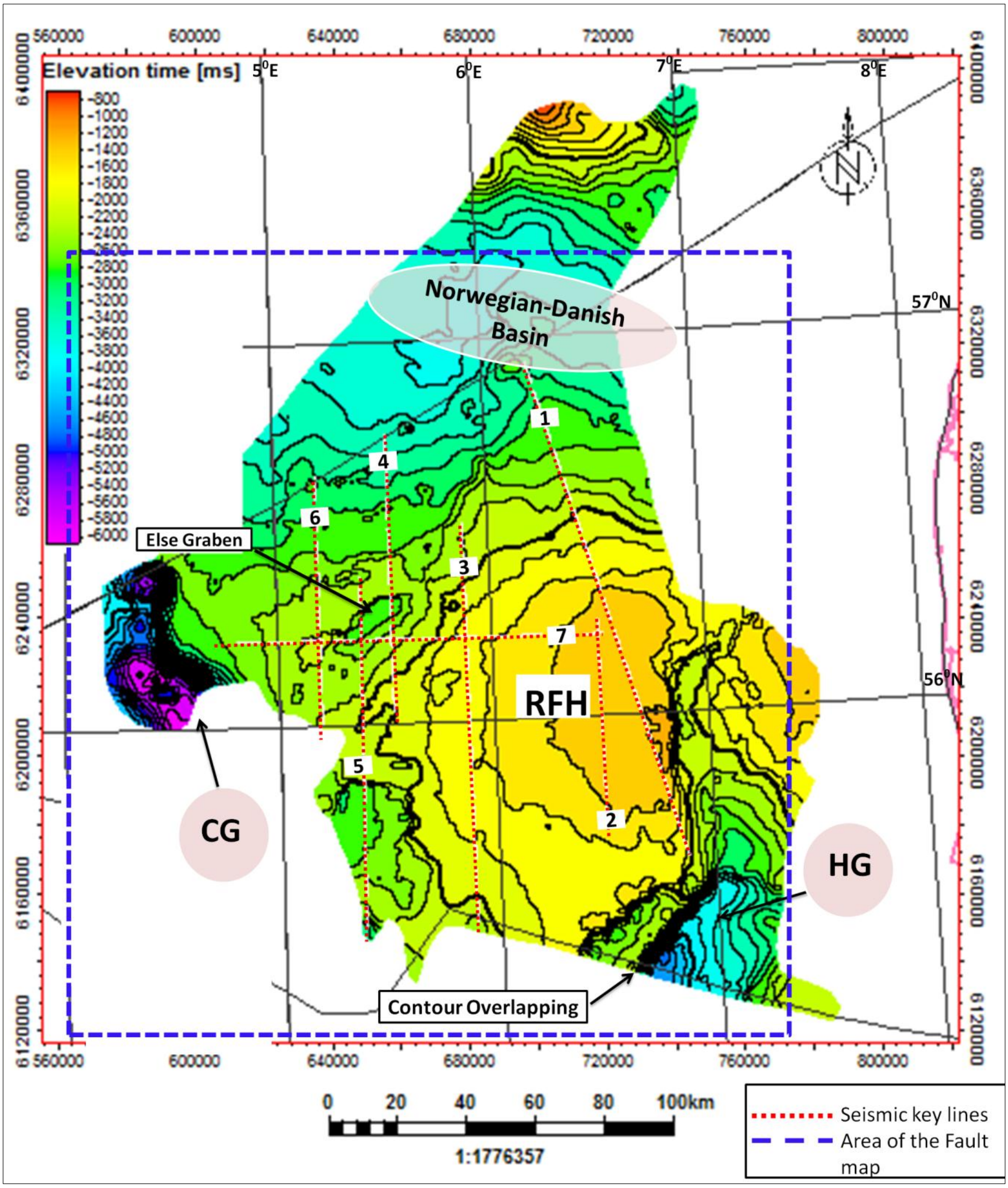


Figure. 4.9. Time-structure map of the Top Rotliegend Group. TWT is in ms and contour interval is 200 ms. Orange color shows shallowest part and purple color shows deepest part towards west in the Central Graben. The yellow to orange colored area in the center represents Ringkøbing-Fyn-High (RHF) between Horn Graben (HG) in the east and Central Graben (CG) in the west. The deep area in the north of the Ringkøbing-Fyn High is representing the Norwegian-Danish Basin. Seismic key lines are shown by numeric charaters (1-7). The blue rectangle shows the area of the fault map displayed in figure 4.10.

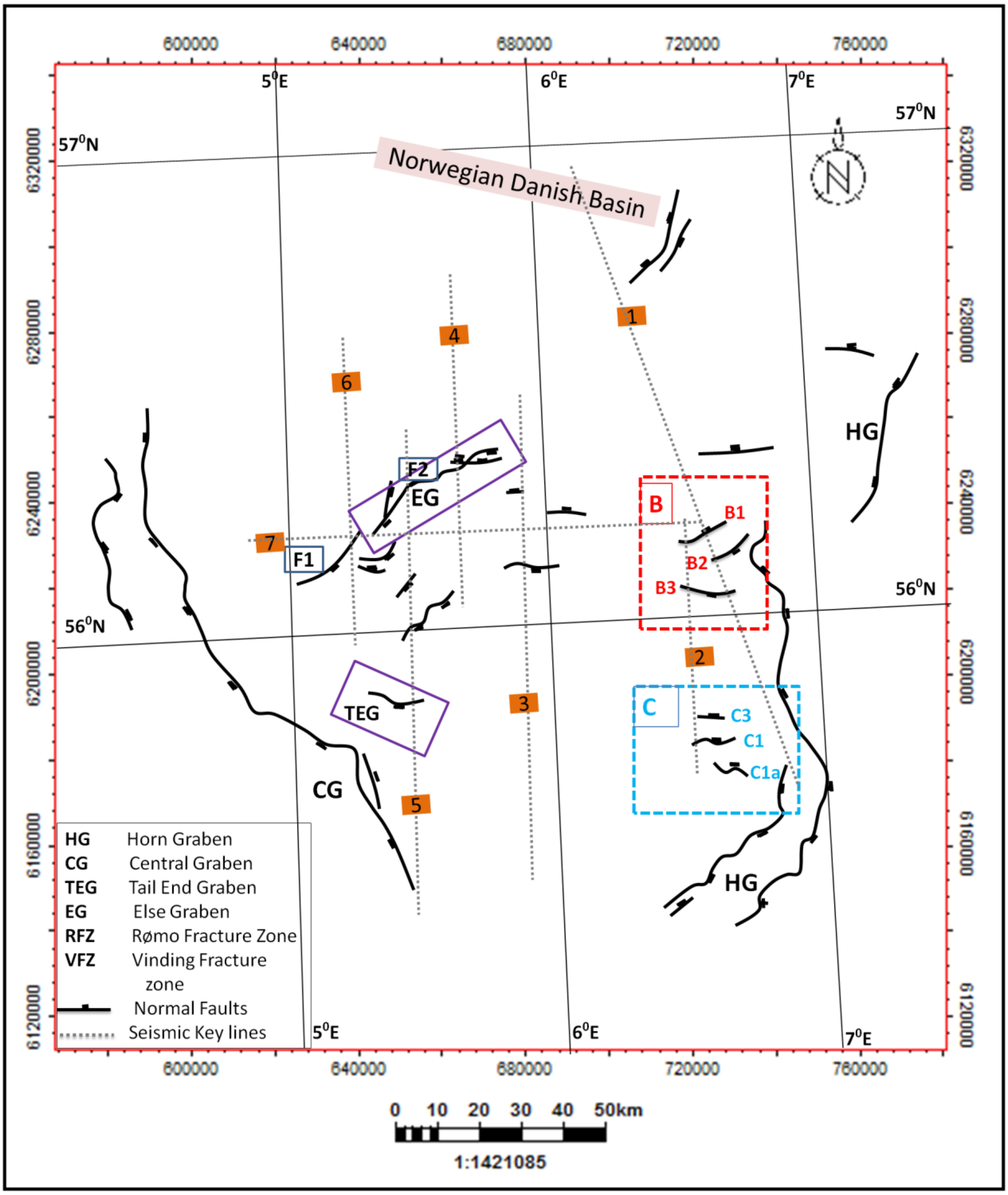


Figure. 4.10. Fault map of the top Rotliegend Group (early-mid Permian) in the study area. Fault segments are shown in the colored rectangles on the map. TEG and EG are taken from Cartwright (1990). Seismic key profiles are shown in the map as well represented by numeric characters 1-7. The location of the area is shown in figure 4.9 (blue rectangle).

The structural configuration of the Rotliegend Group differs from the top basement rocks in the study area. The fault map of the Rotliegend group shows that the fault segments A, D and E (see *fig. 4.1*) vanish at lower Permian interval (*fig. 4.10*). Over the disappeared fault segments mostly clastic and volcanoclastic deposition is prevailed. The faults of the segment C also start becoming less pronounced at this interval and gradually disappear upwards.

A general agreement between time-structure map (*fig. 4.9*) and fault map (*fig. 4.10*) can be established. The fault map at early-mid Permian level explains the trends of the major faults with vertical displacement directions mainly on the Ringkøbing-Fyn High. Both northern (westward dipping) and southern (eastward dipping) segments of the Horn Graben display a general N-S trend. A smaller mapped part of the Central Graben shows a common NW-SE strike direction. Segment B (B1, B2 & B3) defines a strike of NE-SW direction (e.g. B1 & B2) in the north and towards south strike of the faults become E-W (e.g. B3) similar to as observed in figure 4.1. A set of faults C3, C2 & C1a (segment C) in the southeastern corner demonstrate E-W strike (e.g. C3) to nearly SE-NW (e.g. C1a) trend of the normal faults (*fig. 4.10*).

The Else Graben can be identified with a NE-SW strike direction making a half-graben geometry. An array of smaller normal faults between Else Graben and Tail End Graben is seen with a general NE-SW orientation. Apparent dip of the faults is to the SE way. A dispersed existence of the fault segments, around the Ringkøbing-Fyn High at the early-mid Permian level, leaves a stable uplifted area in the middle making an interesting structural high.

Overall, the occurrence of the faults is mcuh less concentrated at early-mid Permian level than at basement interval but configuration of the faults is identical.

4.4.2. Zechstein Group (late Permian)

The late Permian Zechstein Group is mapped in the areas of the Norwegian- Danish Basin (NDB) adjacent to Ringkøbing-Fyn High (RFH) and a smaller part between the Central Graben (CG) and Ringkøbing-Fyn High. It confirms absence over the Ringkøbing-Fyn High and presence in the Norwegian-Danish Basin (*fig. 4.11*).

The color differences in the time-structure map at this level satisfactorily display profound depth towards north in the Norwegian- Danish Basin and shallowness to the south (*fig. 4.11*). It also reveals the increase in the size of the salt domes as we move towards northern part of the Norwegian- Danish Basin. The southern margin of the Zechstein salt makes nice onlaps over the Rotliegend Group (*fig. 4.5, 4.7 & 4.8*).

The generation of the time-structure map at late Permian interval assists to demarcate the boundary between the Ringkøbing-Fyn High and Norwegian-Danish Basin. To some extent, southern termination of the Zechstein salt is corresponding to the northern flank of the Ringkøbing-Fyn High.

At some places salt has displaced due to overburden and thickness of the Zechstein Group becomes zero. In the time-structure map, it is not possible to eliminate those areas from the map due to software obstacle. But, areas of zero thickness are obvious in the time-thickness map of the Zechstein Group (*fig. 4.12*). The fault map of the Zechstein Group has not been prepared for its tendency of being beyond the scope of the present study.

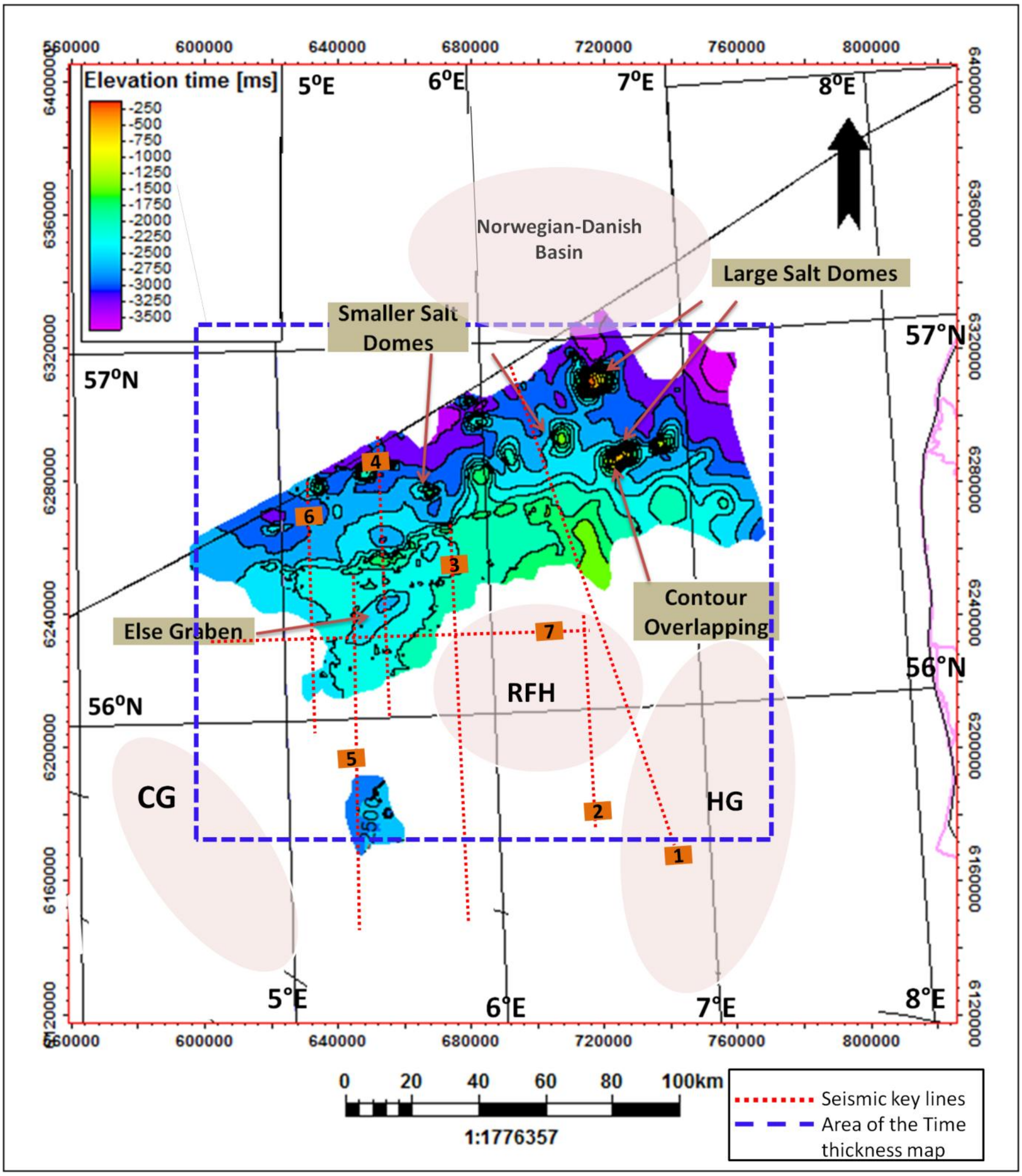


Figure. 4.11. Time-structure map of the top Zechstein Group (late Permian). TWT is in ms and contour interval is 250ms. Green color shows shallowest parts towards southeast and purple color shows deepest parts towards north. RFH: Ringkøbing-Fyn-High, HG: Horn Graben, CG: Central Graben. The deep area in the north represents the Norwegian-Danish Basin. Seismic key lines are shown by numeric charaters (1-7). The blue square is the area of the time-thickness map of the Zechstein Group displayed in figure 4.12.

4.4.3. Time-thicknessm map of the Zechstein Group

Time-thickness map for the late Permian Zechstein Group is generated to examine the thickness variations in the interpreted area. It is obvious from the color disparity that thickness of the salt is much higher in the Norwegian-Danish Basin with an absence over the Ringkøbing-Fyn High. A gradual increase in the thickness from south to north is noticed. An abrupt change in color (purple) in the northern part confirms the presence of the thick salt diapirs. As mentioned above (4.4.2) that at places, thickness of the salt becomes zero basinward. In the time-thickness map, it is possible to distinguish the areas of absence of the salt (*fig. 4.12*). The time-thickness map for the Rotliegend Group in the study area was not created due to missing lower boundary surface.

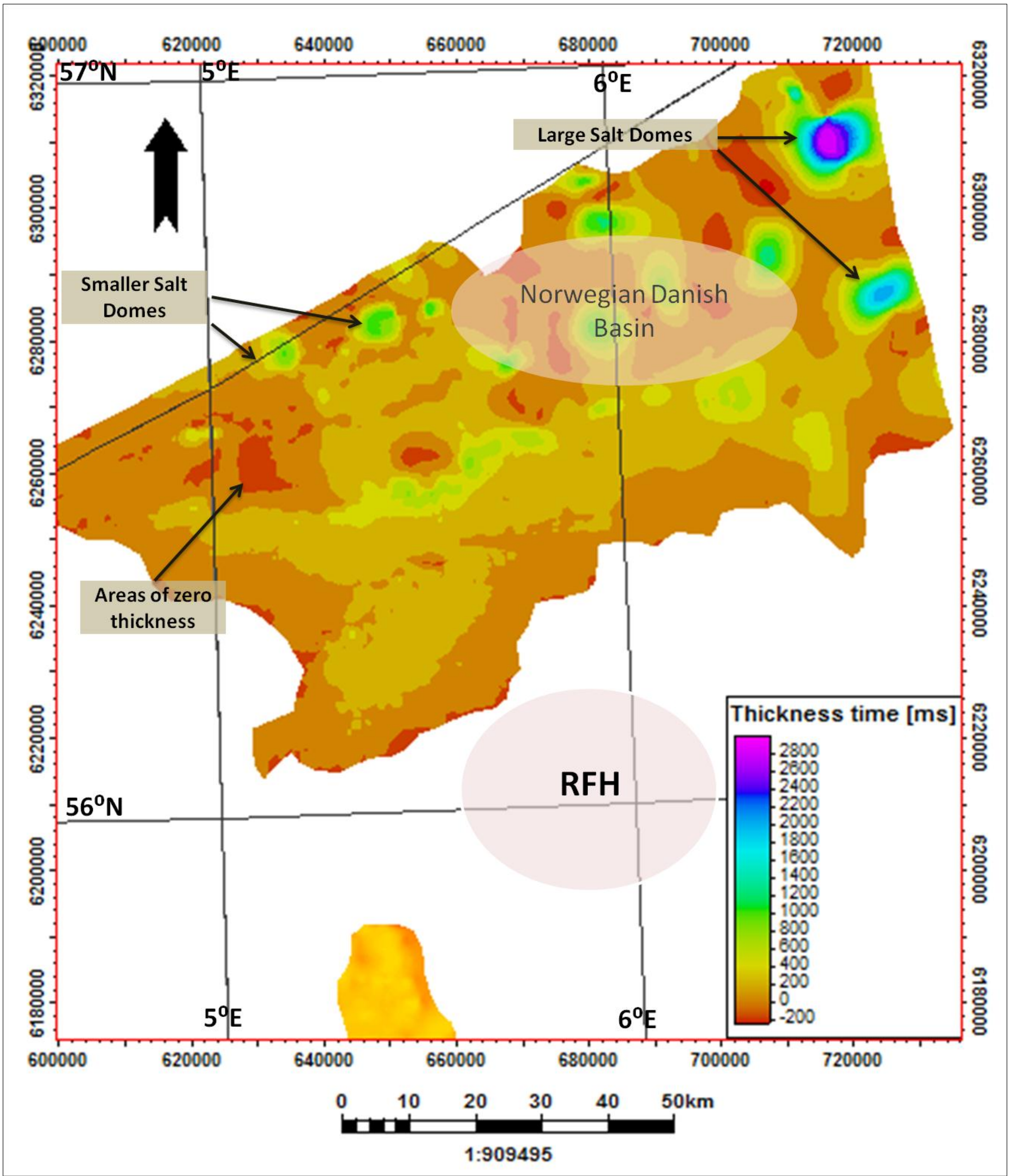


Figure. 4.12. Time-thickness map of the late Permian Zechstein Group. TWT is in ms. Purple color shows thick parts to the north and orange color shows areas of less thickess in the south. The southeastern boundary of the salt is analogous to the northern limit of the Ringkøbing-Fyn-High (RHF). The location of the map is shown in figure 4.11 (blue rectangle).

4.4.4. Base Chalk Group (early late-Cretaceous)

The base Chalk Group is mapped mainly over the Ringkøbing-Fyn High and neighboring areas which comprise parts of the Central Graben, the Horn Graben and the Norwegian-Danish Basin (*fig. 4.13a*). The time-structure map of the base Chalk Group do not show complex structural variations at early late-Cretaceous interval. It depicts a gradual deepening towards WSW direction. The deeper values of the two way travel time (twt) are observed in the area of the Central Graben. Over the Horn Graben and Ringkøbing-Fyn High, base Chalk Group also deepens towards WSW direction following the general trend in the study area. The eastern part of the study area is relatively shallow as compared to the central and western parts. At places in the Norwegian-Danish Basin, the base of the Chalk Group is disturbed by salt diapirs and is not mapped in smaller areas over the diapirs (*fig. 4.13a*).

The fault map at early late-Cretaceous interval shows few main faults including boundary faults of the Central Graben, Horn Graben and two major faults J1 and J2 dipping towards each other (*fig. 4.13b*). The main fault of the Central Graben strikes NW-SE with an apparent southwest dip direction. The boundary fault of the Horn Graben contains both northern and southern segments having a general N-S orientation. The apparent dips are towards east for the southern segment and towards west for the northern segment. The faults J1 and J2 make a large Graben structure at early late-Cretaceous level and show a ENE-WSW trend. The graben structure is confirmed on the key seismic line 6 (*fig. 4.7*). Few normal faults with little lateral extent are observed in the northern part making small grabens seen on the key seimic line 1 (*fig. 4.2*). Other smaller normal faults are present close to the northwestern boundary of the Ringkøbing-Fyn High. The general strike of these faults is NE-SW with an apparent southeast dip direction.

4.4.5. Top Chalk Group (late Cretaceous)

The time-structure map of the top Chalk Group covers the Ringkøbing-Fyn High and parts of the Central Graben, Horn Graben and Norwegian-Danish Basin. It shows more or less same configuration as base Chalk Group. A general deepening trend is towards WSW. The Central Graben can be distinguished easily with a sudden increase in the depth to the western side. The eastern and northeastern area is relatively shallow as compared to the west. An erosional valley is observed close to the northern boundary of the Ringkøbing-Fyn High (*fig. 4.14a*) which is confirmed on the seismic line 5 and 6 (*fig. 4.6 & 4.7*) . The effect of the salt diapirs in the Norwegian-Danish Basin is also visible at this time-interval.

The frequency of the faults declines at late Cretaceous level. The main boundary fault of the Central Graben disappears in the southwestern part and only northern part of the fault retains its position in the study area. J1, J2 and main faults of the Horn Graben show their presence at the specific time interval with ENE-WSW and N-S strike directions respectively. No faults have been observed over the Ringkøbing-Fyn High (*fig. 4.14b*).

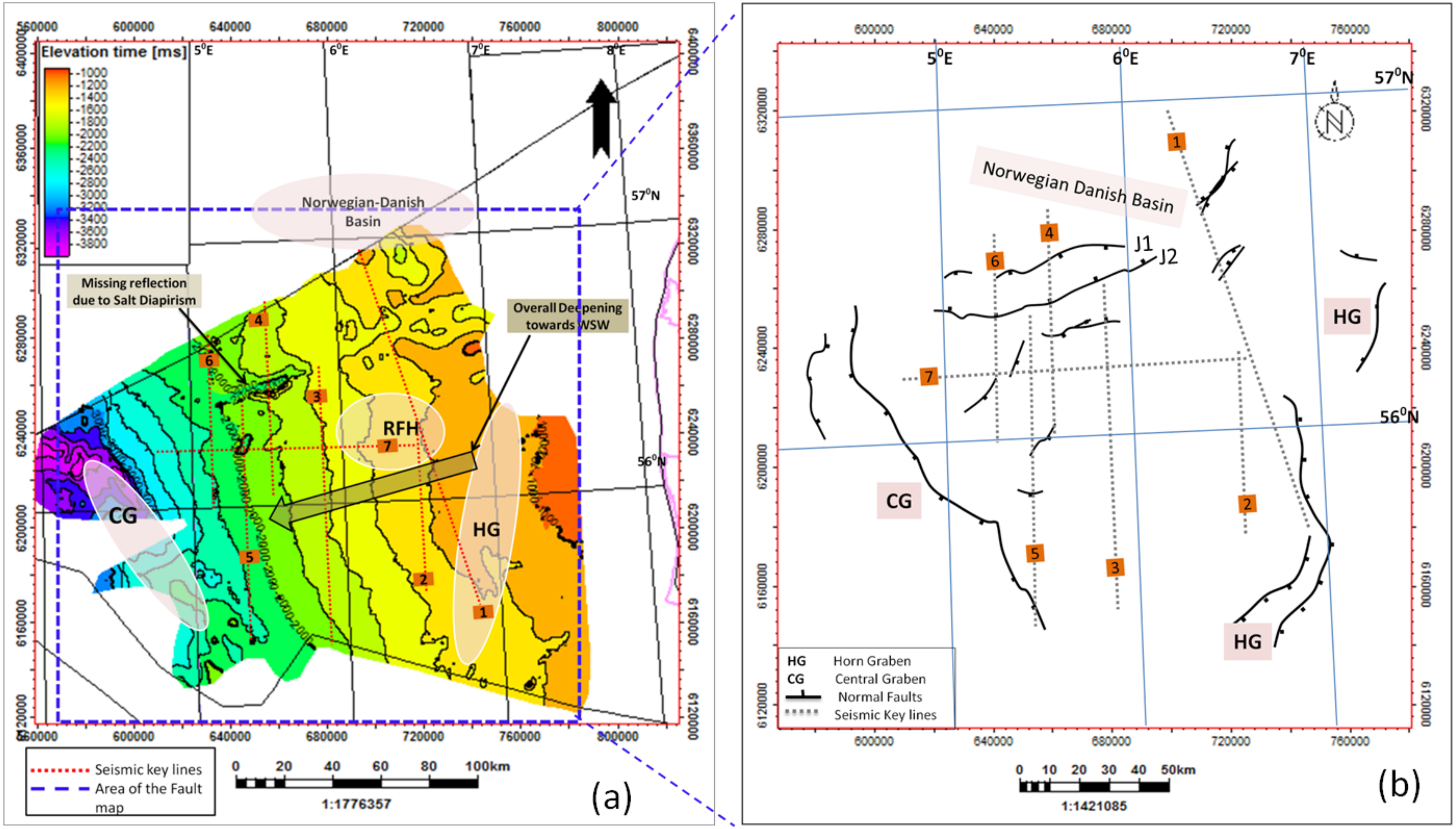


Figure .4.13: (a) Time structure map of the Base Chalk Group (late Cretaceous). TWT is in ms and contour interval is 200ms. Orange color shows shallowest part towards east and purple color shows deepest part towards southwest. **(b)** Fault map of the Base Chalk Group (late Cretaceous) in the study area. RHF: Ringkøbing-Fyn-High between, HG: Horn Graben and CG: Central Graben. Seismic key lines are shown by numeric characters (1-7). The blue square is the area of the Fault map of the Base Chalk Group displayed in the figure 4.13(b).

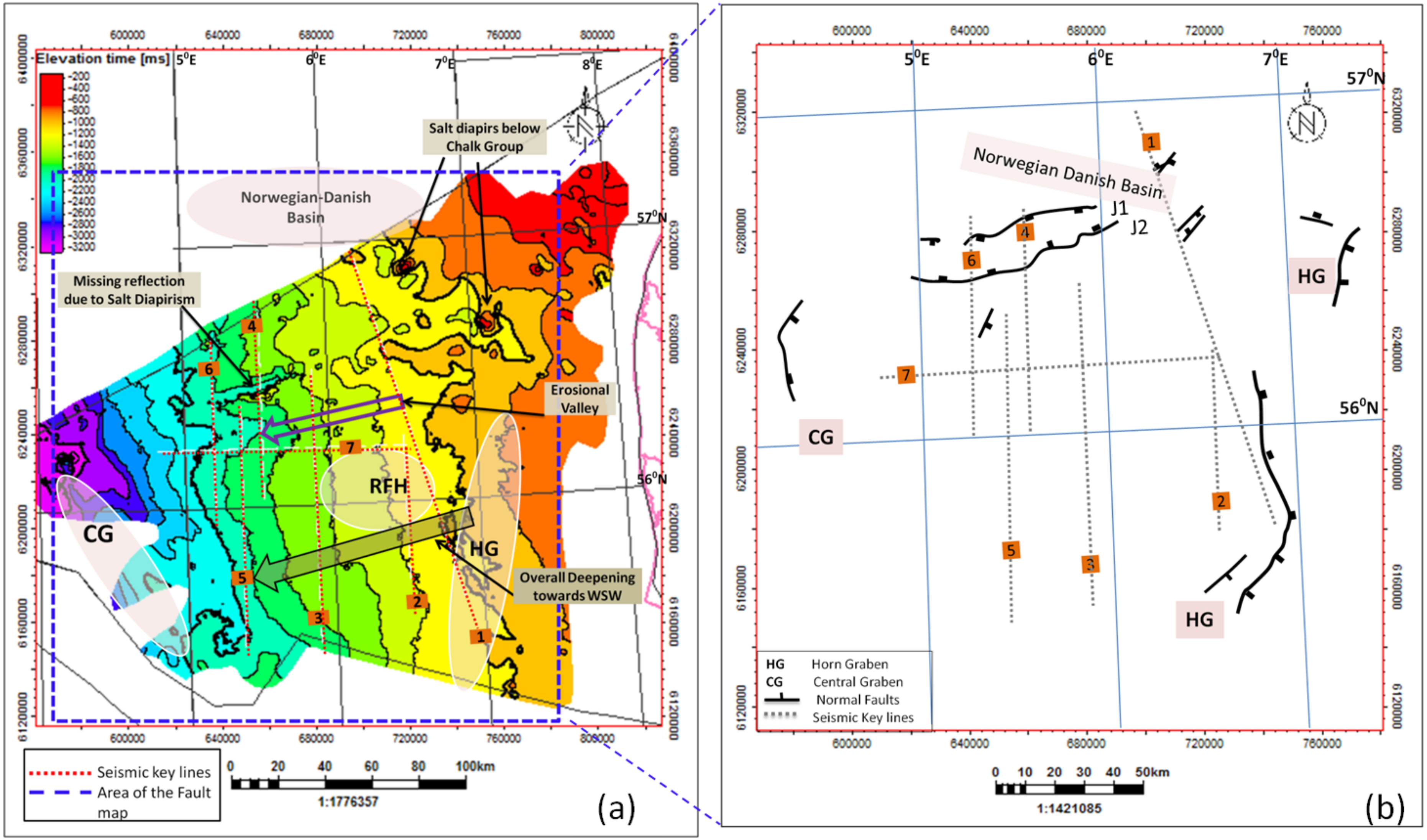


Figure .4.14: (a) Time structure map of the top Chalk Group (late Cretaceous). TWT is in ms and contour interval is 200 ms. Red color shows shallowest part towards northeast and purple color shows deepest part towards southwest. **(b)** Fault map of the top Chalk Group (late Cretaceous) in the study area. Seismic key lines are shown by numeric characters (1-7). The location of the fault map area is shown in the figure 4.14a (blue rectangle). RHF: Ringkøbing-Fyn-High between, HG: Horn Graben, CG: Central Graben.

4.4.6. Time-thickness map of the Chalk Group (late Cretaceous)

The time-thickness map of the Chalk Group shows a variation in thickness across the study area. In general, thickness of the Chalk Group is increasing away from the Ringkøbing-Fyn High almost towards all the directions (*fig. 4.15*). An abrupt change in the color towards west separates the Central Graben from the Ringkøbing-Fyn High. The maximum thickness is noticed in the Central Graben. Over the Ringkøbing-Fyn High, the Chalk Group contains minimum thickness. A gradual increase in thickness from Ringkøbing-Fyn High towards Horn Graben is visible. The stratigraphic package is also thinner at the place of an erosional valley observed on the time-structure map (*fig. 4.14a*).

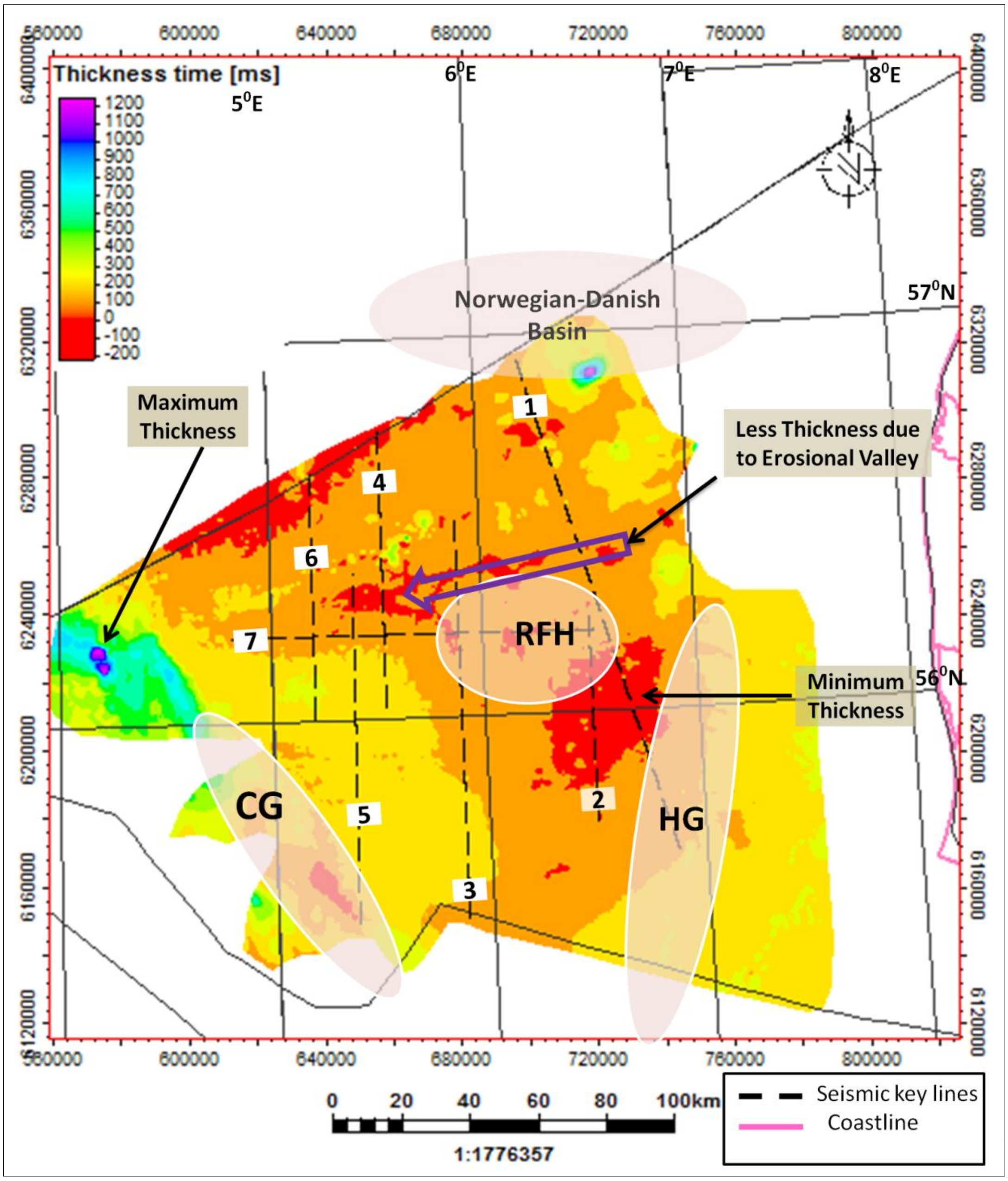


Figure. 4.15. Time-thickness map of the Chalk Group (late Cretaceous). TWT is in ms. Purple color shows thick parts towards southwest and red color shows areas of minimum thickness on the Ringkøbing-Fyn High and in the erosional valley. Seismic key lines are shown by numeric charaters (1-7).

CHAPTER 5

DISCUSSION

It has been one of the most debated questions in geology of the southeastern North Sea concerning when and how the Ringkøbing-Fyn High was formed. Several attempts have been made to find out the genesis and age of the relatively uplifted structure in the region. The detailed description of the structural features has already been presented in chapter 4. In this chapter, structural architecture in relation to regional tectonics of the study area, primarily Ringkøbing-Fyn High, will be brought under discussion on the basis of the seismic interpretation elaborated in chapter 4 and literature review. In addition, fault geometries and genesis, the age of the sediments in the wedges, fault dating and reactivation of the faults, unconformities and the northern boundary of the Ringkøbing-Fyn High by correlating the Bouguer gravity anomaly data are discussed.

As structural evolution of the Ringkøbing-Fyn High is discussed earlier by others, a brief introduction of the work done by the previous authors is given below:

1) Ziegler (1982) suggested that this positive structure was created during the late Carboniferous-early Permian times of the regional extensional tectonics (as cited in Cartwright, 1990).

2) Cartwright (1990) also suggested that the Ringkøbing-Fyn High was formed during late Carboniferous-early Permian tectono-magmatic episode.

3) Vejbæk (1997) stated that the Ringkøbing-Fyn High suffered lesser stretching than contiguous basins during the pre-Zechstein rifting which formed the Ringkøbing-Fyn High (as cited in Clausen and Pedersen, 1999).

4) Zhou & Thybo (1997) gave an opinion that the Ringkøbing-Fyn High could be formed during or after deposition of the Rotliegend.

5) According to Scheck et al. (2002), the East North Sea High (or Ringkøbing-Fyn High) is a Palaeozoic inverted rift.

The study area is mainly characterized by extensional tectonic episodes from the late Palaeozoic to Mesozoic eras. At certain levels, uplifting (inversion?) has modified the extensional structures in the area which enhance the complexity of the structures. In order to get best possible understanding, the area is divided laterally into different fault segments based on distinct fault geometries and trends.

5.1. Fault Geometries and Genesis

The Ringkøbing-Fyn High and adjacent Norwegian Danish Basin are characterized by extensional fault systems striking ESE-WNW to E-W to ENE-WSW to NE-SW (*fig. 4.1*). These different trends are probably attributed to differences in (σ_2- σ_3) horizontal principle stress differential and pre-existing basement weakness (Davison, 1994). Lateral and vertical fault geometries are discussed below:

5.1.1. Fault configurations in map view

The lateral configuration of the faults can be seen in figure. 4.1. These sets of faults are divided into different segments. Segment A strikes at NE-SW to E-W direction which explains the northern limb of a probable graben system (*fig. 4.4*). Faults in segment B show an orientation of NE-SW to E-W direction describing SE to S tilted half-grabens. Segment C displays faults having ENE-WSW to ESE-WNW trend. These faults show an array of half-grabens located on the southern boundary of the Ringkøbing-Fyn High. Segments B and C demonstrate conjugate fault orientations dipping towards central unlikely uplifted block. The ESE-WNW striking fault segment D is characterized by NNE rotated fault blocks displaying a half-graben setting (e.g. D2 & D3). The E-W striking faults of segment E define a zone of half-grabens delineating the northern boundary of the Ringkøbing-Fyn High. The normal faults are widely spaced in segment E. The study area can be characterized by overlapping unlinked normal faults following Davison (1994). On the basis of evidences from seismic interpretation, it is seen that all the faults drawn on the top basement fault map penetrate upward into Rotliegend Group excluding D1 & D3 (*fig. 4.1*). This provides grounds to use the basement fault map to represent the late Carboniferous-early Permian time interval.

Overall, the study area is defined by laterally complex fault geometries. Ziegler (1990) proposed that during late Carboniferous-early Permian dominent direction of the extension was east-west (as cited in Scheck et al., 2002). It is very uncertain that WSW-ENE to west-east oriented half-graben would have been formed during east-west extension (Scheck et al., 2002). Heeremans & Faleide (2004) argued that half-grabens filled with clastic and volcanoclastic material were created due to transtensional tectonics. Also, evidences for the strike-slip movement are hard to be found in the study area based on the seismic reflection data.

5.1.2. Vertical fault geometries

The detailed analysis of the fault geometries along dip dimension does not show large variations in the study area (*fig. 5.1*). The stratigraphic succession from top basement to top Rotliegend Group in the study area is mainly deformed by extensional tectonics and for the most part, faults are restricted to below top Rotliegend Group. It is observed that fault geometries in the south differ from the fault geometries in the north in sense of the size and presence of the Palaeozoic succession in the wedges (*fig. 5.1b & 5.1c*). This difference might be attributed to the erosion on the crests of the half-grabens due to differential uplifting of the Ringkøbing-Fyn High.

The fault maps of the top and base of the Chalk Group show that during late Cretaceous, the Ringkøbing-Fyn High became tectonically stable (*fig, 4.13b & 4.14b*).

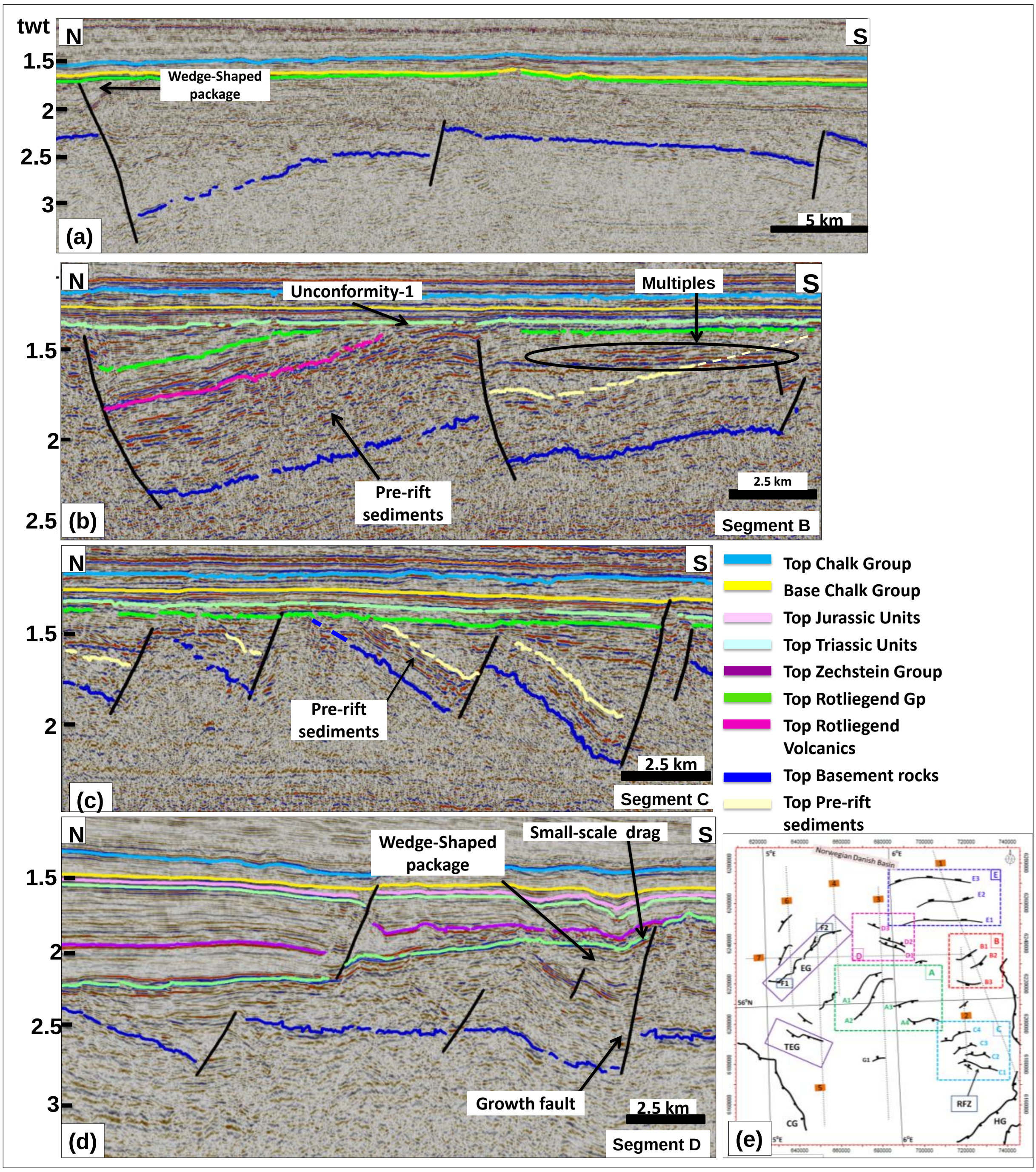


Figure. 5.1. (a), (b), (c) & (d) 2D seismic lines showing the fault geometries of the late Carboniferous-early Permian interval. (e) Location map of the fault segments. Legends for mapped horizons are shown in the top right corner .

5.1.2.1. Late Carboniferous-early Permian interval

This time interval is characterized mainly by different sets of steeply dipping to slightly curved to listric normal faults, developed by extesion at that time interval. The southern part of the Ringkøbing-Fyn High (*5.1c*) is characterized by rather steeply dipping normal faults as compared to the northern parts (*fig. 5.1b*). The deposition of the lower Permian sediments in the syn-rift settings indicates that the extension took place at the start of the Permian succession. Also the radiometric age of the lower volcanics of the Rotliegend Group proves the late Carboniferous-early Permian rifting at c. 300 Ma (Heeremans et al., 2004a). Growth faults are also observed in the study area. The sediments are thickening on the hanging walls towards the half-graben bounding faults. It may represent contemporaneous stretching and subsidence stages (*fig. 5.1d*). It is very common to see the tilted fault blocks over the Ringkøbing-Fyn High and in the adjacent areas of the Norwegian-Danish Basin. The direction of rotation of the fault blocks during syn-rift stage is shown by Gabrielsen (2010) (*fig. 5.2A*). The geometry of the sediments in the wedges (*fig. 5.1a, 5.1c & 5.1d*) is analogous to the idealized section of Prosser (1993) to some extent (*fig. 5.3*). A small-scale drag on the hanging wall in the shallow part of the syn-rift strata probably shows simultaneous rifting and deposition (*fig. 5.1d*).

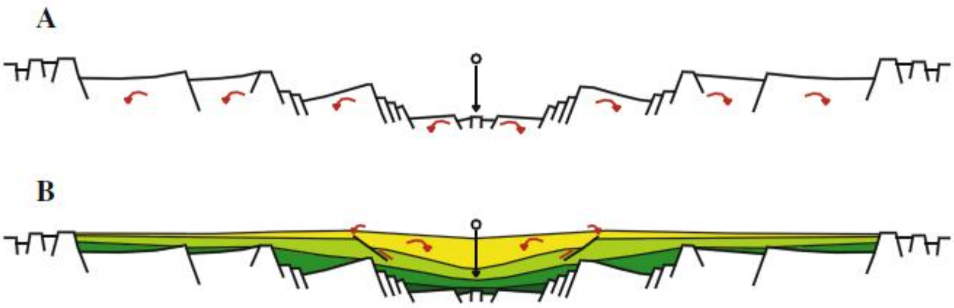


Figure. 5.2. General Behavior of the sedimentary strata during (A) syn-rift (B) post-rift stages (after Gabrielsen et al. 2010).

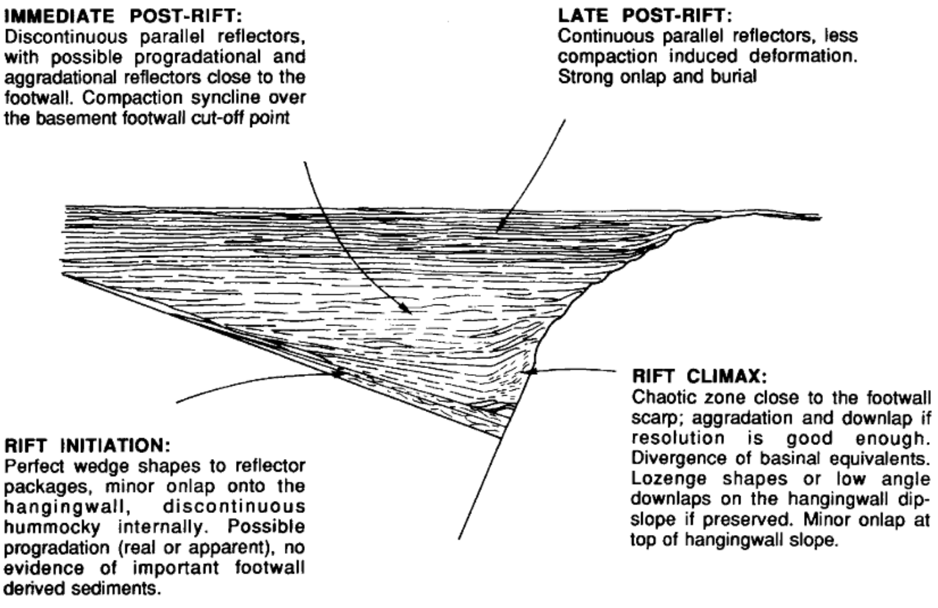


Figure. 5.3. A line drawing through an ideal seismic section (after Prosser, 1993).

In the southwestern area of the Ringkøbing-Fyn High few older planar normal faults have been observed at lower Palaeozoic interval which do not penetrate to upper Palaeozoic succession (*fig. 5.1a*). They might have been developed by an older extensional event in the region e.g. extension during Devonian (Ziegler, 1990a; Viejo et al., 2002). Such kinds of faults are not found in the northeastern part of the Ringkøbing-Fyn High and in adjacent areas of the Norwegian-Danish Basin.

5.2. Constraining the age of syn-sedimentary wedges

Presence of the pre-Permian sedimentary cover under the Norwegian-Danish Basin and over the Ringkøbing-Fyn High in the rotated fault blocks is confirmed by seismic reflection data and is supported by Bouguer gravity anomaly data. However, their ages are still not confirmed. Identification of the stratigraphic contact between the pre-Permian sequence and the Permian Rotliegend Group in the study area is much more complicated, unless constrained by well control. However, on the basis of seismic behavior of the reflections parallel to upper and lower strata, their ages have been bracketed.

The Palaeozoic succession is thicker in the northern part of the Ringkøbing-Fyn High (*fig. 5.4C*) than the southern margin (*fig. 5.4A*). Two distinct trends of sedimentary strata between the Rotliegend Group and the basement are visible. The syn-rift sedimentary strata are parallel to the top Rotliegend reflection and belong to the Rotliegend Group (*fig. 5.4A & 5.4B*). The pre-rift sedimentary strata parallel to the top basement reflection found in the tilted half-grabens resemble the lower Palaeozoic strata of the Skagerrak Graben interpreted by Heeremans & Faleide (2004) (*fig. 5.5*). The lower Palaeozoic strata comprises of Cambro-Ordovician, Silurian platform series and Upper Silurian (lowermost Devonian) clastic sedimentary sequence towards the onshore Oslo Graben (Heeremans & Faleide., 2004). Probably, a similar age of the early Palaeozoic can be assigned to the pre-rift succession in the study area (*fig. 5.4C*).

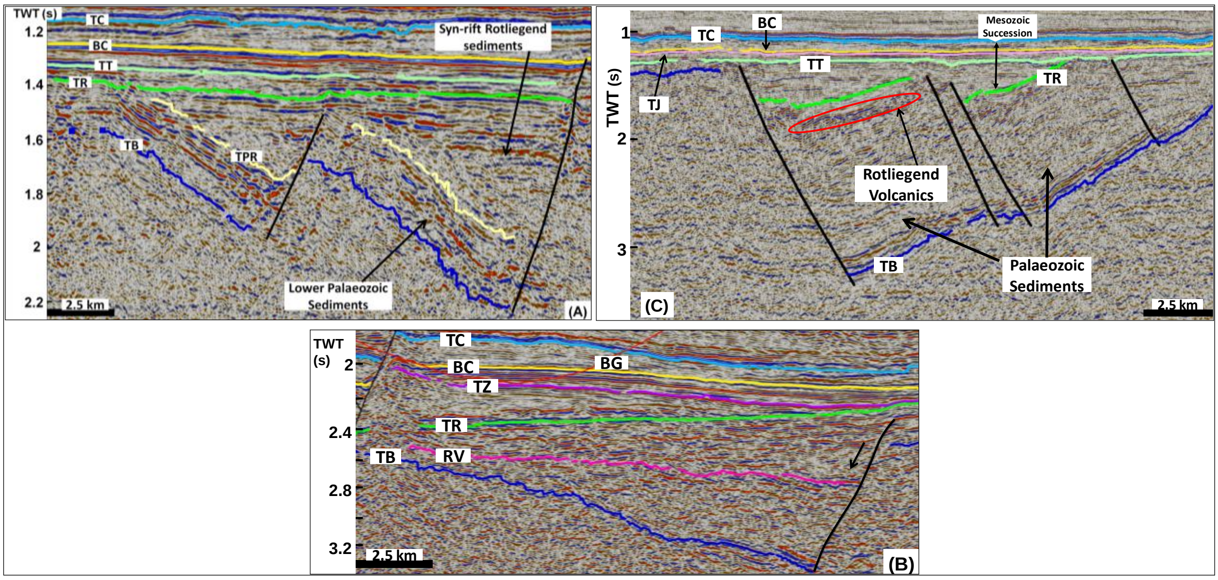


Fig. 5.4. (A) And (C) Seismic sections from the Ringkøbing-Fyn High. (B) From the Norwegian-Danish Basin. TB: Top Basement, TPR: Top pre-rift succession, RV: Rotliegend Volcanics, TR: Top Rotliegend Group, TT: Top Triassic, TJ: Top Jurassic, BC: Base Chalk Group, TC: Top Chalk Group, BG: Bouguer gravity anomaly data curve.

In general, sedimentary sequence parallel to the near-basement reflection are termed as of Palaeozoic age which obtain thickness of up to 4 km below the Horn Graben (2 second 'twt' Vp Avg: 4km/s) but they are evidently thin on the East North Sea High and on the margins of the Mesozoic grabens. This sedimentary succession is located below an unconformity between lower tilted blocks and the overlying sequence (Scheck et al., 2002).

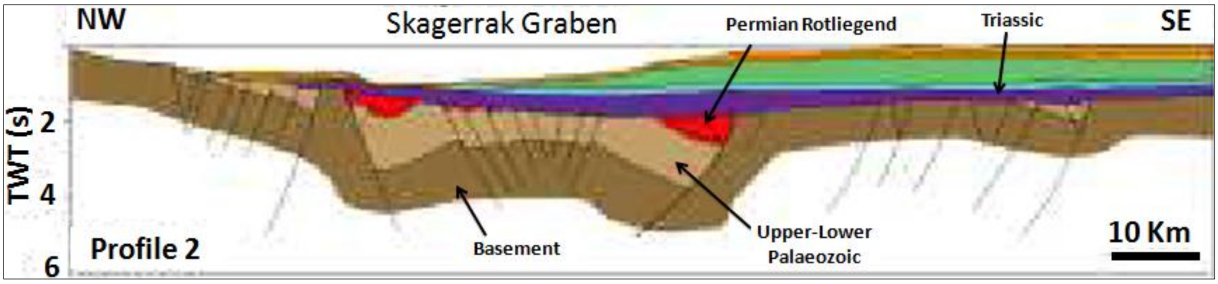


Figure. 5.5. A seismic profile through Skagerrak Graben (modified from Heeremans and Faleide, 2004)

Nielsen et al. (2005) estimated the Palaeozoic succession between 1-4 km on the Mid North Sea-Ringkøbing-Fyn High (MNRFH) on the basis of interpretation of the velocity image and the coincident normal-incident section, which is identical with the assessment of Zhou and Thybo (1997).

In the present study, up to 1500 twt thick Palaeozoic sedimentary sequence has been interpreted in the half-grabens towards the northern sector of the Ringkøbing-Fyn High. In the southern part, this succession attains maximum thickness of up to 450 twt. Towards the Skagerrak area, Vejbæk (1990) interpreted 1000-1500 ms (twt) thick Palaeozoic sedimentary sequence in the down faulted half-grabens. They correspond to almost 2 kilometers (*fig. 5.6*). Half-grabens of similar configuration have been interpreted over the Ringkøbing-Fyn High and in the adjacent Norwegian-Danish Basin (*fig. 5.4A*).

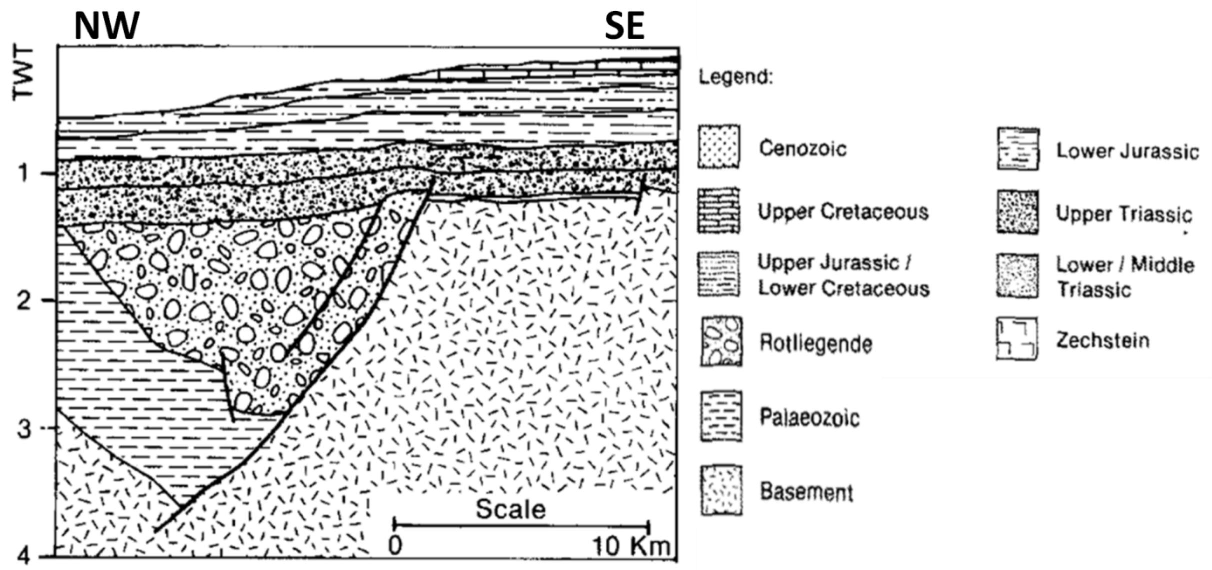


Figure. 5.6. Cross-section from Skagerrak area. It is believed that fault complex is a part of the Oslo Graben-Bamble Trough complex (modified from Vejbæk, 1990).

Towards the shoulders of the Horn Graben and the Central Graben, presence of the Palaeozoic sedimentary rocks is not verified in the study area. They must be very thin or missing due to rift shoulder uplift and erosion throughout the Triassic (Nielsen et al., 1998; Scheck et al., 2002).

The pre-rift succession might consist of thin layers of Carboniferous or Devonian age as the Carboniferous rocks are confirmed on the Grensen Nose in the west of the study area (Maynard et al., 1997; Gerling et al., 1999 and Martin et al., 2002). The sequence lying over the Ringkøbing-Fyn High is almost parallel to the basal sequence over the whole offshore area of the Ringkøbing-Fyn High. The upper part of the sequence is locally discontinuous but regionally extensive and has a character of high frequency-high amplitude seismic facies which is comparable to the Coal Measures successions in the Southern Gas Basin of the North Sea. It is confirmed from drilling that a Middle Devonian to Late Carboniferous succession is present on the Mid North Sea High (Cartwright, 1990). Towards far northeast, upper Carboniferous deltaic sediments with minor marine incursions are reported in the Oslo Graben as well (Olaussen, 1981).

The interpretation of the seismic reflection data confirms the presence of the Palaeozoic sedimentary succession in the study area. The structural similarity between the Ringkøbing-Fyn High and the Mid North Sea High permits to expect thin Devonian to Late Carboniferous sequence over the Ringkøbing-Fyn High while in the adjacent Norwegian-Danish Basin presence of this succession is still unknown. The models by Nielsen et al. (2000, 2005) also verify the Palaeozoic succession of up to 4 km thickness over the Ringkøbing-Fyn High (as cited in Lyngsie & Thybo, 2007).

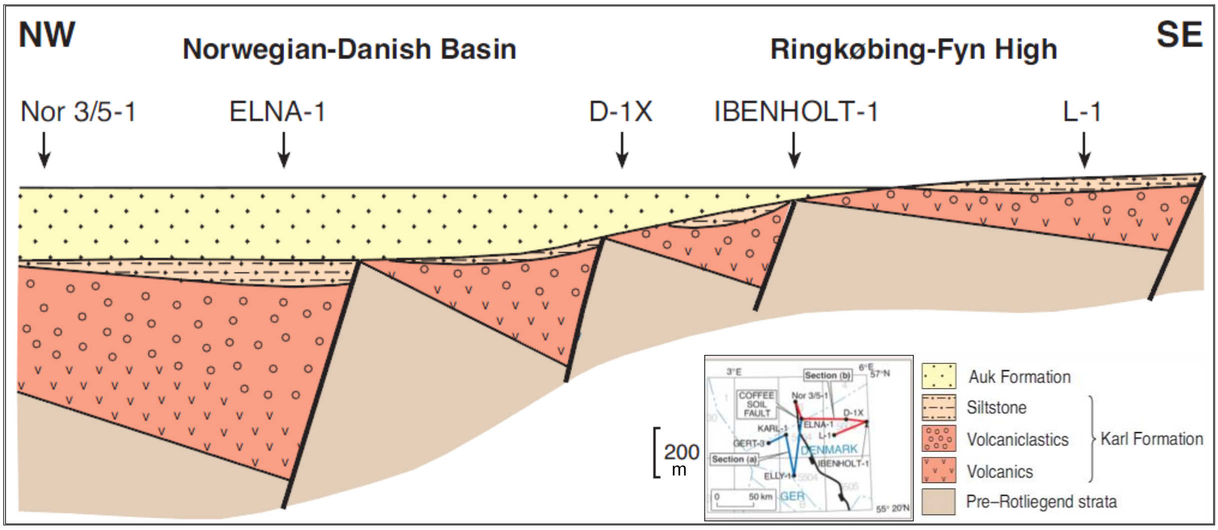


Figure. 5.7. A generalized cross section through the Norwegian-Danish Basin and the Ringkøbing-Fyn High. Auk Formation is onlapping the syn-rift volcanic and sedimentary rocks (modified from Glennie et al., 2003).

Towards the Oslo Graben and the Kattegat areas, Heeremans & Faleide (2004) suggested volcanoclastic material of early Permian age deposited in the syn-rift settings. Based on the structural similarity between the half-grabens, similar Rotliegend volcanics have been interpreted in the study area (*fig. 5.4C*). The interpretation of this succession in the half-grabens in the study area slightly differs from the generalized cross section illustrated by Glennie et al. (2003) (*fig. 5.7*).

5.3. Unconformities (erosional surfaces in the study area)

Several erosional surfaces have been recognized in the study area, which are consistent with the previous work undertaken by several authors. These unconformities are present over the horsts and crests of the rotated fault blocks. Over the Rinfkøbing-Fyn High, erosion of the sedimentary succession is much pronounced as compared to the Norwegian-Danish Basin which can be attributed to uplift of the Ringkøbing-Fyn High. The maximum erosion has been observed over the horsts in the study area e.g. H1 and H2 (*fig. 4.2 & 4.4*).

The following unconformities are recognized in the study area.

i. Unconformity-1: is representing hiatus from early-mid Permian to late Triassic (equivalent to Saalian Unconformity) (*fig. 4.3 & 5.1b*).
ii. Unconformity-2: is representing hiatus from mid-Permian to early Jurassic (equivalent to Base Jurassic Unconformity) (*fig. 4.8 & 5.2A*).
iii. Unconformity-3: is representing hiatus from late Permian to early Cretaceous (equivalent to Base Cretacous Unconformity) (*fig.4.7 & 5.9B*)
iv. Rotliegend Unconformity (*fig. 5.1.*) (Scheck et al., 2002).

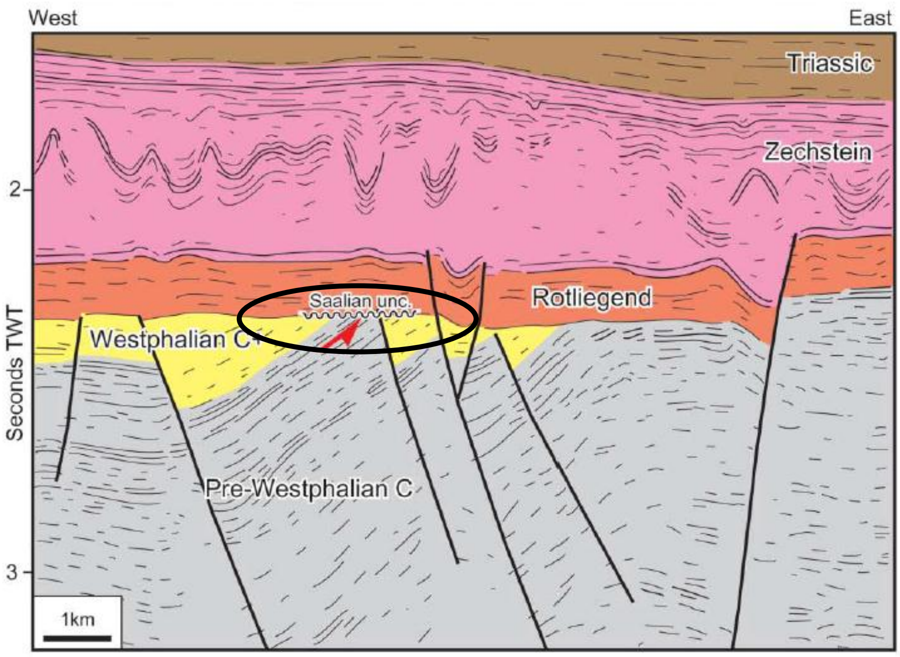


Figure. 5.8. A geoseismic section in the northern part of the Southern North Sea showing the Saalian unconformity in the marked circle (modified from Martin et al., 2002).

On the Ringkøbing-Fyn High probable Rotliegend volcanics are truncated under the late Triassic succession making an angular relationship based on seismic evidence. In the study area this is named as Unconformity-1 (*fig. 5.1b*). Unconformity-1 might be correlated with a well known erosional unconformity in mid-Permian times that has been identified throughout the Variscan foreland called the Saalian unconformity (*fig. 5.8*) (Heward & Reading, 1980; Fraser & Gawthorpe, 1990; Leeder & Boldy, 1990; Serrane, 1992; Hollywood & Whorlow, 1993; Michelsen & Nielsen, 1993; Quirk & Aitken, 1997; Roberts et al., 1999; Martin et al., 2002). At places, it has been noted that a stratigraphic succession at the base of the Jurassic units is missing (Unconformity-2) which means some of the areas of the Ringkøbing-Fyn High were exposed to erosion in early Jurassic times (*fig. 5.9A*). This unconformity is well known in the literature and has been marked by earlier workers such as Clausen & Korstgård (1993, 1994). In agreement with Cartwright (1990), Clausen and Korstgård (1993, 1994) marked a major unconformity at the base of Jurassic sequence in the area of the Horn Graben (Clausen and Pedersen, 1999).

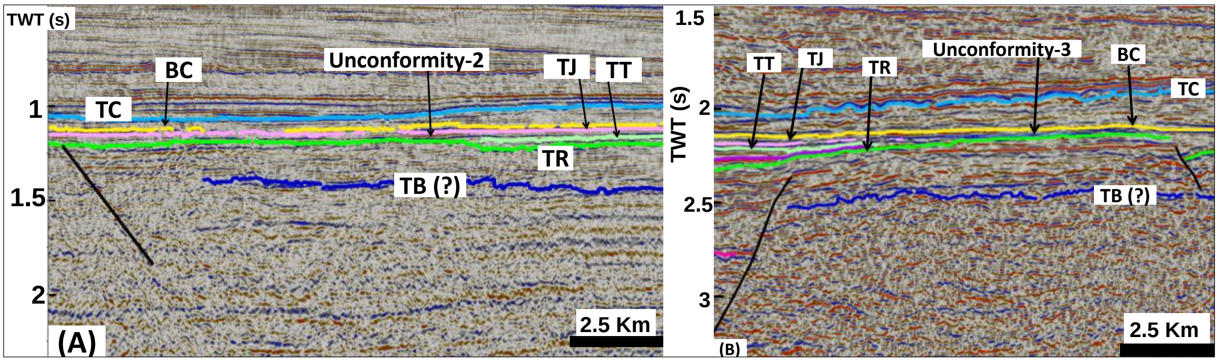


Figure. 5.9. Unconformities over the Ringkøbing-Fyn High (A) Unconformity-2 and (B) Unconformity-3. TB: Top Basement, TR: Top Rotliegend Group, TT: Top Triassic, TJ: Top Jurassic, BC: Base Chalk Group, TC: Top Chalk Group.

Similarly, the Unconformity-3 in the study area is observed at places which represents the missing succession from late Permian to early Cretaceous (*fig. 5.9B).* Besides the deeper basins in the North Sea, an unconformity generally known as the "late Cimmerian Unconformity" (or "base Cretaceous Unconformity" is present at places (Johnson, 1975; Ziegler, 1975; Rawson and Riley, 1982). The origin of most of the unconformities in the North Sea is eustatic, even in the tectonically active parts of the North Sea, the eustatic sea level changes were never entirely prevailed by local tectonics (Rawson and Riley, 1982).

Scheck et al. (2002) in agreement with Abramovitz & Thybo (1999) marked a regional unconformity named as the Rotliegend Unconformity (*fig. 5.10A*), which extends to the Norwegian-Danish Basin, the Ringkøbing-Fyn High and the Horn Graben. The dipping reflections of the lower Palaeozoic sequence truncate along this unconformity (*fig. 5.10 A & 5.10B*).

This unconformity can be identified on the seismic sections in the study area as shown in figure 5.10B.

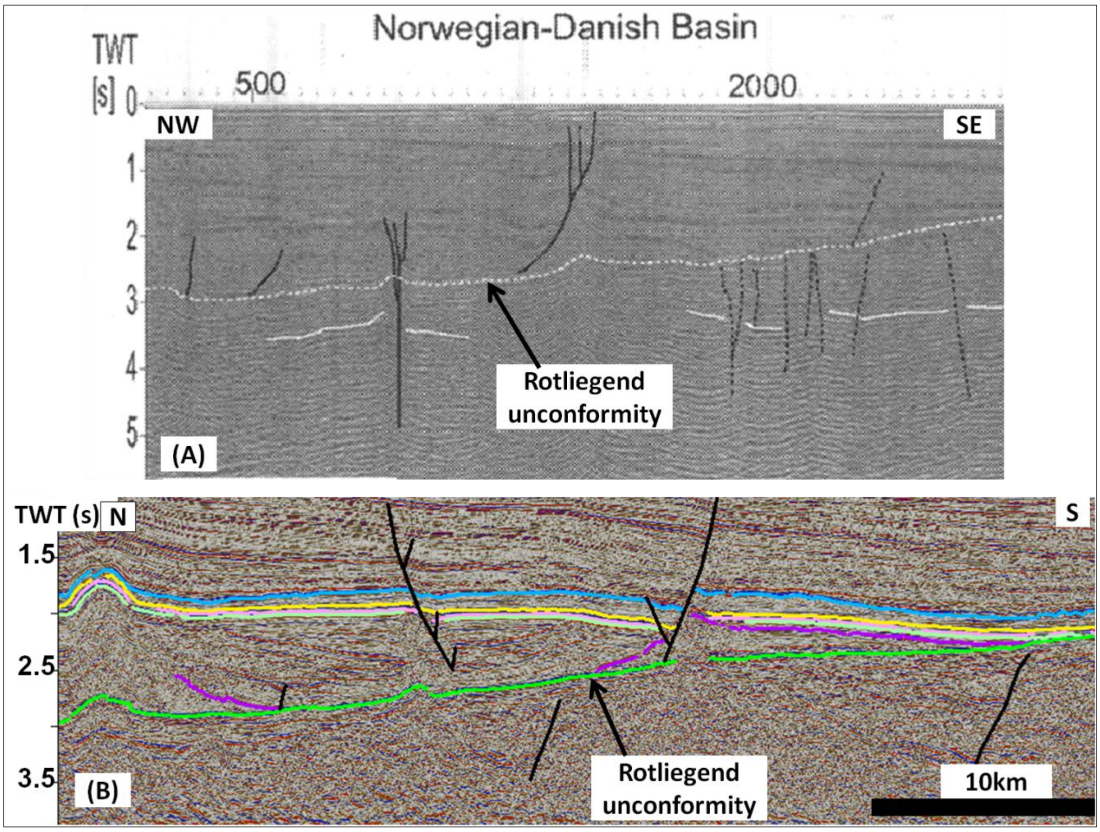


Figure. 5.10. Seismic sections through Norwegian-Danish Basin. Both (A) (modified from Scheck et al., 2002) and (B) display Rotliegend Unconformity in the basin.

5.4. Fault Dating and Re-activation

In order to understand the structural evolution of the study area, stratigraphic fault dating and reactivation of the faults have been analyzed. Generally, the age of the faults can be established with the help of stratigraphic dating i.e. by considering the ages of affected or unaffected rock formations. In case of syn-depositional faults, the age of the formation is contemporaneous to that of the faulting (Angelier, 1994).

The area of interest regarding the fault dating was the northern side of the Ringkøbing-Fyn High. A seismic section from the north of the Ringkøbing-Fyn High has been selected for the stratigraphic dating (*fig. 5.11C*). The northward dipping faults in figure 5.11C have been interpreted on the seismic key line 1 (*fig. 4.2*). These E-W striking normal faults terminate below top Rotliegend Group and do not penetrate the late Permian Zechstein Group. The syn-rift strata are parallel to the top Rotliegend Group which gives some clue to constrain the age of faulting (*fig. 5.11C*). These syn-rift packages belong to the early-mid Permian Rotliegend Group. Thus, an age of early Permian similar to the age of the syn-rift strata can be assigned to these faults based on the stratigraphic dating. To utilize the Expansion (growth) Index method was not possible to resolve the issue of fault dating due to erosion of the sedimentary succession on the footwalls.

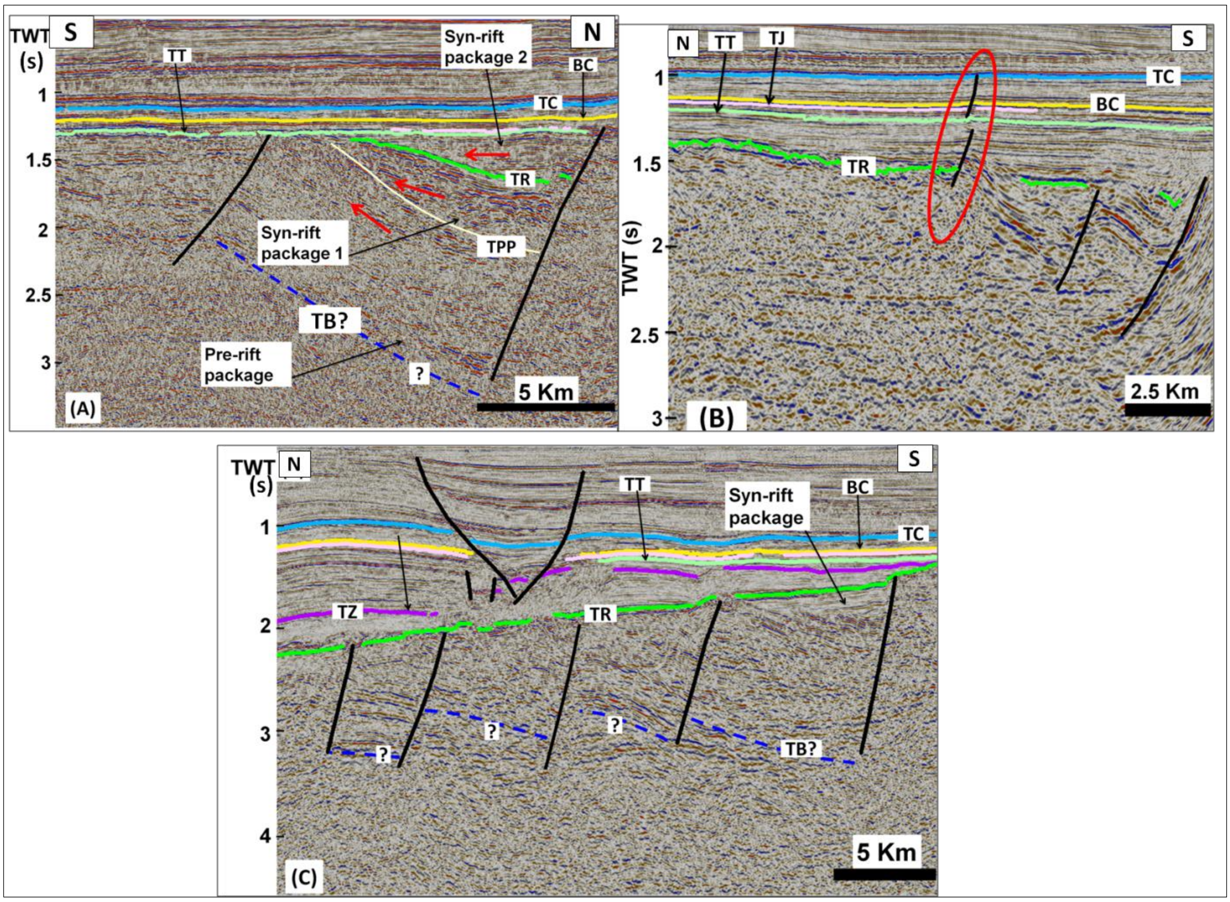


Figure. 5.11. Seismic section through the Ringkøbing-Fyn High (A) from northern part of the RFH (B) from the southern part of the RFH (C) A seismic section representing the northern boundary of the RFH towards Norwegian-Danish Basin. TB: Top Basement, TR: Top Rotliegend Group, TZ: Top Zechstein Group, TT: Top Triassic, TJ: Top Jurassic, BC: Base Chalk Group, TC: Top Chalk Group.

It has been noted that at places few of the faults have been reactivated during younger rifting events such as the fault in the red circle (on *fig. 5.11B*). The tendency of the faults to reactivate is concentrated close to the Horn Graben (*fig. 5.11A*) which might be attributed to the late Permian-early Triassic rifting of the Horn Graben mentioned by Beha et al. (2008) in agreement with Clausen & Korstgård (1993).

The red arrows in figure 5.11A clearly define the three different trends of the sequences. These trends explain that the Permian fault was reactivated during Triassic rifting event. Based on these trends, three ages can be estimated:

i. Pre-rift package (the lower Palaeozoic package parallel to the basement)
ii. Syn-rift package 1 (related to Permian rifting)
iii. Syn-rift package 2 (related to Triassic rifting)

The red circle in figure 5.11B shows two different periods of fault reactivation. Both faults in the circle are closely related to each other. On the basis of stratigraphic offsets it can be deduced that the fault under consideration experienced initial movement in Triassic and later on was reactivated probably during the mid-late Cretaceous representing a cyclic kinematic behavior.

Additional fault reactivation in the study area might be attributed to the perpendicular strike directions of the Palaeozoic faults to the Permo-Mesozoic faults of the Horn Graben (Scheck et al., 2002). For the Palaeozoic extensional faults, Lyngsie & Thybo (2007) argued that the basement faults of Caledonian age were reactivated during the late Carboniferous-early Permian rifting which formed sub-basins and half-grabens.

5.5. Northern Boundary of the Ringkøbing-Fyn-High (A Comparison of the Seismic Data with Bouguer Gravity Anomaly Data)

The northern boundary of the Ringkøbing-Fyn High can be seen in the previously published maps (e.g. Cartwright, 1990). Another attempt has been made to demarcate it based on the following combinations:

i. Time-structure map of the top Rotliegend Group and time-thickness map of the Zechstein Group
ii. Extensional faults in the basement and Bouguer gravity anomaly data

The interpretation of the seismic reflection data in the study area has led to mark the extensional faults in the basement. By positioning these faults over the Bouguer gravity anomaly data map, an acceptable correlation can be found between them. On the hanging walls of the normal faults, the decrease in the values of the gravity data confirms the accuracy of the seismic interpretation (*fig. 5.12A*). The higher values of the Bouguer gravity anomaly data in a limited area allow demarcating the border of the Ringkøbing-Fyn High.

Figure 5.12B clearly shows that the upper Permian Zechstein salt is onlapping the Ringkøbing-Fyn High towards northern and northwestern flanks of the Ringkøbing-Fyn High. Later, a thin sequence of the Triassic age is found to be present over the Ringkøbing-Fyn High at places which means this structure was exposed to erosion until the late Permian. So, northern boundary of the Ringkøbing-Fyn High is marked where the Zechstein salt is pinching out (*fig. 5.12B*). By positioning this boundary on the gravity data map (combined with basement faults), an acceptable match can be found.

After gaining the northern boundary, it can be inferred that horst H1 should be the part of the Ringkøbing-Fyn High (*fig. 5.12A*).

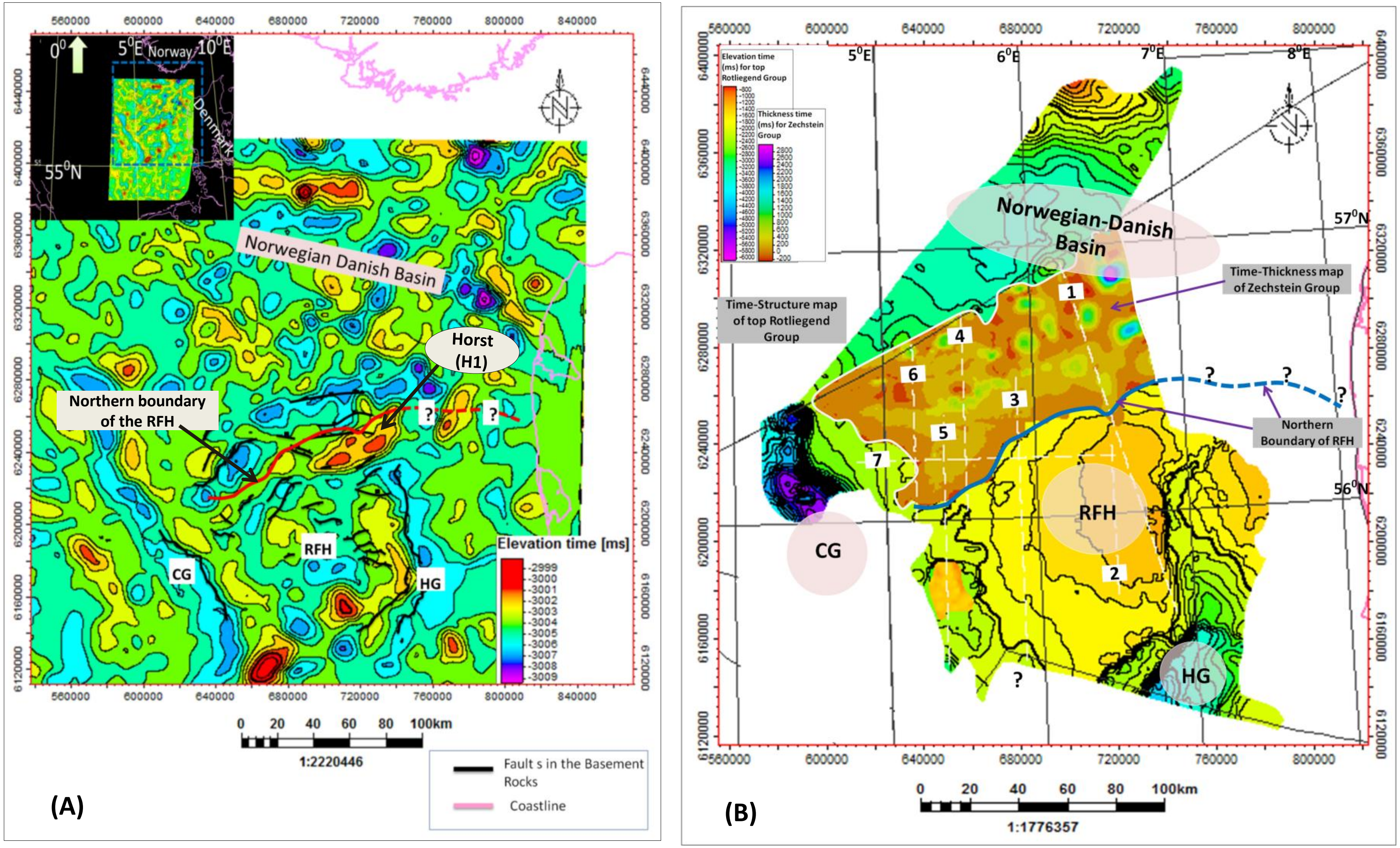


Figure. 5.12. Northern Boundary of the Ringkøbing-Fyn High (A) 50 km High Pass Filtered Bouguer gravity anomaly data combined with basements faults. The gravity data was adjusted to the seismic time values. (B) Time-structure map of the top Rotliegend Group combined with time-thickness map of the Zechstein Group. RHF: Ringkøbing-Fyn High, CG: Central Graben, HG: Horn Graben.

5.6. Geological Evolution of the Ringkøbing-Fyn High and the Adjacent Norwegian-Danish Basin

There is an agreement on the late Carboniferous-early Permian regional volcanism in the North Sea but relative uplifting of the Ringkøbing-Fyn High has been explained differently by previous workers. Regionally, topography of the near basement horizons in the Danish North Sea is labeled by two major fault sets: Palaeozoic faults with WSW-ENE to E-W strike and Mesozoic faults striking in NNE-SSW to NNW-SSE direction. Following the Caledonian Orogeny, extension as a result of post-orogenic collapse, and later compression and extension initiated by the Variscan Orogeny, might have affected the region (Scheck et al., 2002).

The tectonic map of the North Sea area (from Lyngsie & Thybo, 2007) defines that the Ringkøbing-Fyn High is located on the Caledonian Deformation Front (*fig. 5.13*). During the Caledonian collision (which involved three continents Baltica, Laurentia and Avalonia) in the late Ordovician to early Silurian, a deep foreland basin was formed in the Danish region of Scandinavia (Thybo, 1990; Ziegler, 1990a; Thybo, 2001 and Lyngsie & Thybo, 2007). During Devonian, the Variscan Orogeny also created a distal foreland basin in the central and southern North Sea where several kilometers of the sediments are assumed to have been deposited from the Caledonides (Ziegler, 1990a; Lyngsie & Thybo, 2007). The lower Palaeozoic sedimentary strata found in the study area might belong to these foreland basins (*fig. 5.4a, 5.4b, 5.4c & 5.14*).

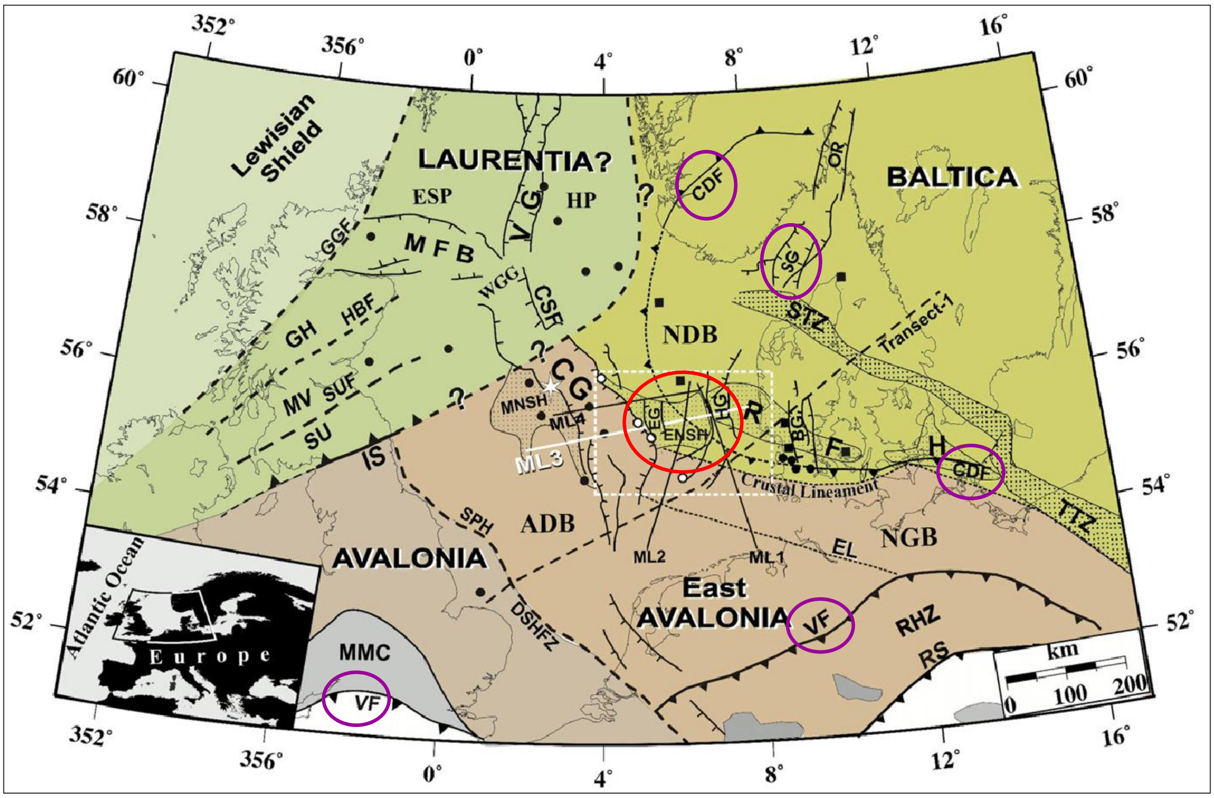


Fig. 5.13. Major tectonic elements in the North Sea. Caledonian Deformation Front (CDF) passes through the area of the East North Sea High (ENSH) (or Ringkøbing-Fyn High) marked by red circle (modified from Lyngsie & Thybo, 2007). VF: Variscan Front; SG: Skagerrak Graben.

After the Caledonian Orogeny, rifting occurred in Devonian times (Zielgler, 1990a; Viejo et al., 2002). Based on the seismic interpretation, it is perhaps difficult to say that the whole study area experienced the Devonian rifting except southwestern part of the Ringkøbing-Fyn High where older extensional faults are observed in a limited area (*fig. 5.14*). They are restricted to the lower Palaeozoic succession. Due to uncertain ages of the Palaeozoic succession, the stratigraphic dating of these faults is not possible. However, it can be said that they belong to another rifting phase older than the late Carboniferous-early Permian rifting event.

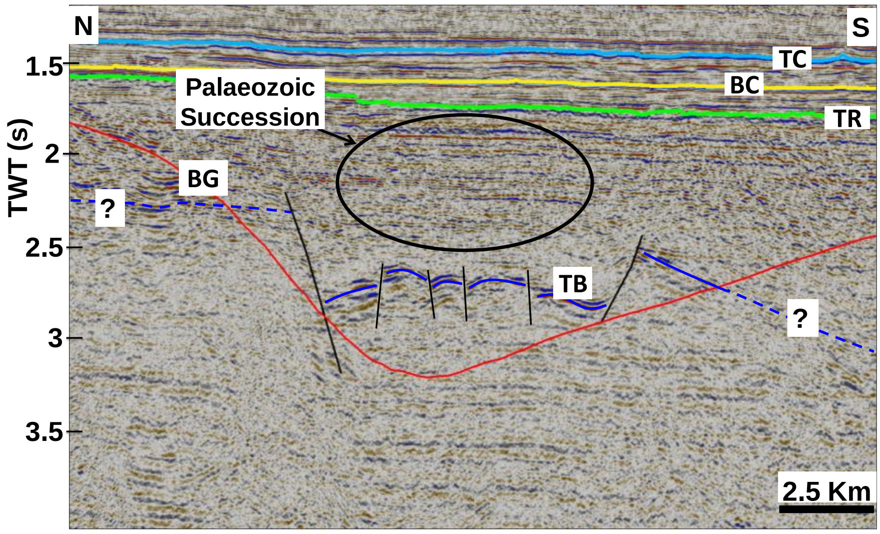


Fig. 5.14. A seismic section from southwestern part of the Ringkøbing-Fyn High. The location of the section is given in figure 3.2. Southern part of the second line in the east of the key line 3. TB: Top Basement, BG: Bouguer Gravity anomaly data, TR: Top Rotliegend Group, BC: Base Chalk Group, TC: Top Chalk Group.

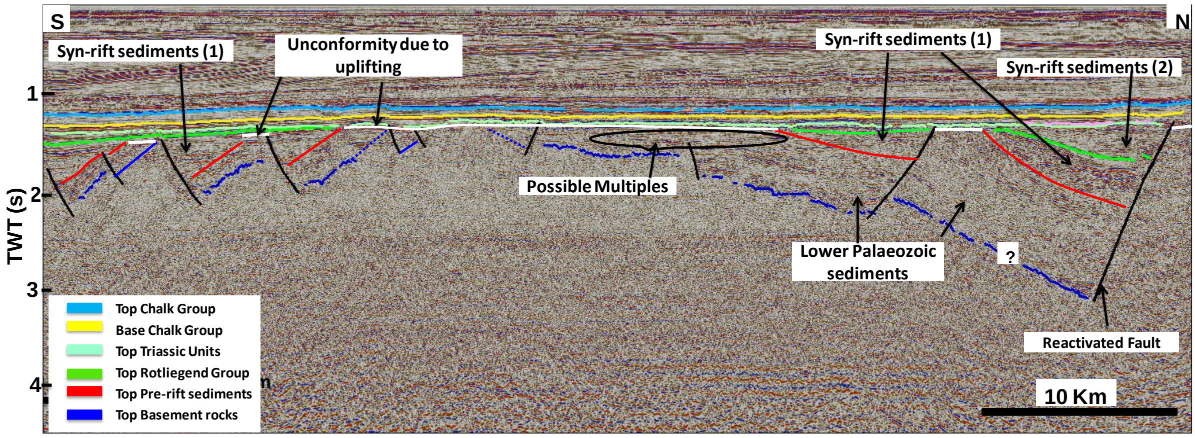


Figure. 5.15. Interpretation of the seismic profile through the Ringkøbing-Fyn High. The location of the line can be seen in figure 3.2. It is the first line in the east of the seismic key line 2.

The presence of the faults is supported by the Bouguer gravity anomaly data curve. The detailed analysis on couple of surrounding seismic lines also reveals that these faults do not continue up to the Rotliegend Group.

Intra-continental rifts of the late Carboniferous times are well known in the NW Europe (Wilson et al., 2004; Torsvik et al., 2008). The trends of Carboniferous-Permian dykes in Sweden, SE Norway and Scotland infer that the center of the regional magmatism was under the Skagerrak area (Ernst & Buchan, 1997; Torsvik et al., 2008). Torsvik et al. (2008) suggested that volcanic rocks of age 297±4 Ma correspond to a Skagerrak Centered Large Igneous Province (SCLIP) based on the palaeomagnetic apparent polar wander (APW) path which generated plumes from the Core Mantle Boundary (CMB).

The interpretation of the seismic reflection data in the study area confirms that the late Permian Zechstein Group is onlapping the northern flank of the Ringkøbing-Fyn High (*fig. 4.2, 4.4 & 4.6*) which at least demonstrates that the Ringkøbing-Fyn High was uplifted before the deposition of the late Permian succession. However, deposition over the Ringkøbing-Fyn High started in the late Triassic as thin beds of the succession have been noticed at places. It shows that the structure remained uplifted until early late-Triassic. Stratigraphic dating of the basement faults in the study area (see under 5.4) along with radiometric dating in the central North Sea (Heeremans et al., 2004a) gives clue that the extensional faulting started in early Permian times.

It is obvious that crests of the half-grabens were eroded due to rotation of the fault blocks and later on rotation might be contemporaneous with uplifting of the area. The structural architecture of the Ringkøbing-Fyn High shows that the geometry of the extensional fault blocks is strongly affected by the uplift (*fig. 5.15*). The absence of the half-grabens in the central part of the Ringkøbing-Fyn High may explain that they were eroded due to uplift which occurred after the rifting had completed or along with the rifting (*fig. 5.15*).

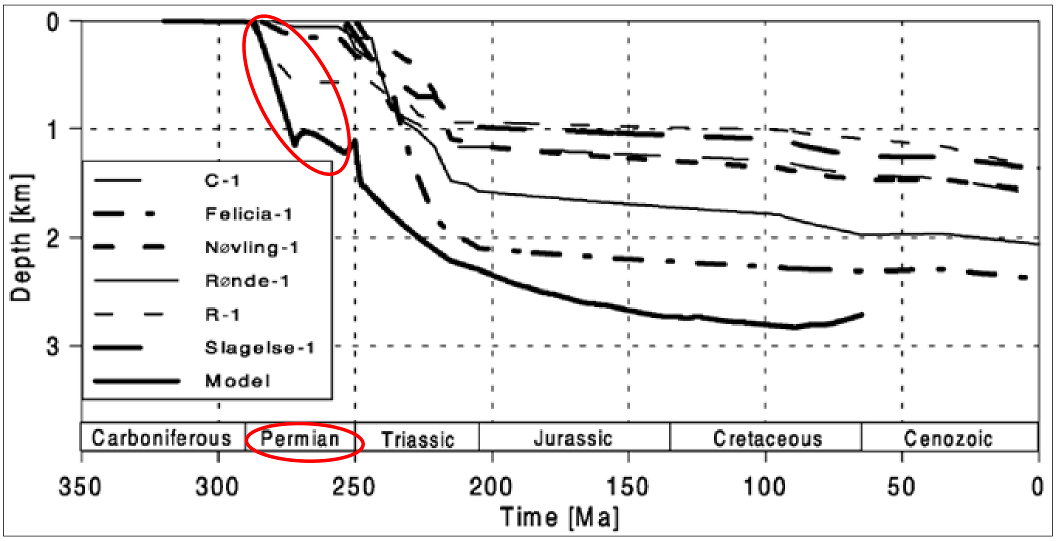


Figure. 5.16. Tectonic subsidence curves of the Norwegian-Danish Basin calculated from the six wells. The red circles show maximum subsidence took place in the Permian time period. Location of the wells is shown in figure 2.1 (modified from Frederiksen et al., 2001).

Thus, the detailed structural analysis of the Ringkøbing-Fyn High allows to suggest that it might have been uplifted between the early Permian to before the deposition of the late Permian Zechstein Group. A reasonable agreement between stratigraphic dating and age of the regional SCLIP (Torsvik et al., 2008) shows that SCLIP might have been the reason for the magmatic underplating (Zhou & Thybo, 1997) resulting into uplift of the Ringkøbing-Fyn High. As a result of uplift, erosion of the Palaeozoic succession took place mainly in the central part of the Ringkøbing-Fyn High and on the crests of the rotated fault blocks (*fig. 5.15*).

After the regional magmatism, the Norwegian-Danish Basin went under substantial thermal subsidence during late Permian and Triassic times (Ziegler,1990; Glennie, 1998; Van Wees et al. 2000; Frederiksen et al. 2001; Heeremans & Faleide, 2004). Also according to numerical modeling results (Frederiksen et al. 2001), the Northern Permian Basin is formed by a thermal event and later on subsidence occurred which created space for the deposition of clastic and evaporitic Zechstein series of the upper Permian (Heeremans and Faleide, 2004). Figure 5.16 explains that there has been considerable subsidence in the Permian and the Triassic time periods as compared to the post-Triassic times. The increased thickness of the late Permian and Triassic sequence in the adjacent Norwegian-Danish Basin also proves a large amount of subsidence due to sediment load (*fig. 4.2 & 4.7*).

Uplift of the Ringkøbing-Fyn High was more pronounced on the southern part as compared to the northern part. It is confirmed from the steeper dips of both the fault planes and the Palaeozoic succession in the South than in the North (*fig. 5.15*). In the South, far from the study area, the Variscan Orogeny generated NW-verging thin-skinned fold and thrust belts in SW Britain (Shackleton et al., 1982; Coward, 1995). However, no direct evidences for the effects of the Variscan compression were found in the study area based on the seismic reflection data.

The detailed analysis of the Cretaceous and Jurassic succession shows that the Ringkøbing-Fyn High and nearby area of the Norwegian-Danish Basin was tectonically stable during Jurassic to Cretaceous times (*fig. 4.13 & 4.14*) except minor fault activity observed in Cretaceous along older faults (*fig.5.11B*). The less thickness of the upper Cretaceous Chalk Group over the Ringkøbing-Fyn High also explains that central part of the structure has remained slightly uplifted till the Cretaceous due to unknown reason (*fig. 4.15*).

A generalized summary of the tectonic evolution of the study area in relation to tectonics of the central North Sea is given in figure. 5.17.

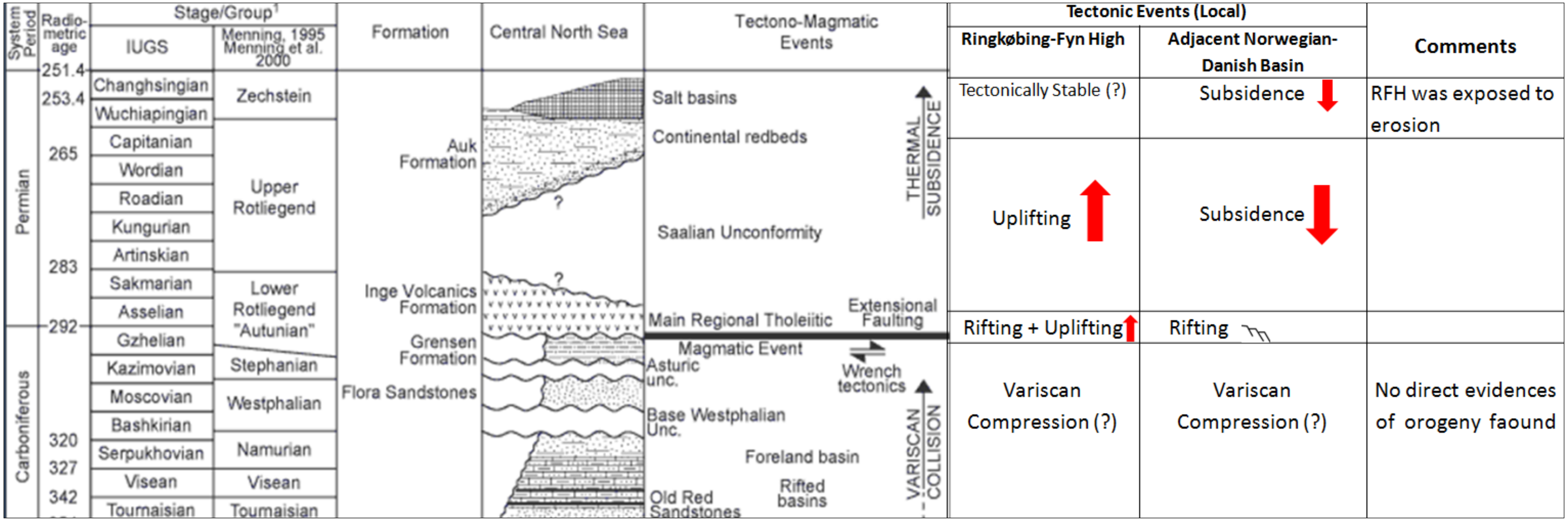


Figure. 5.17. A comparison of the regional Carboniferous-Permian tectonic events in the central North Sea (modified from Heeremans et al., 2004a) with local tectonic events in the study area. The time scales are taken from Menning (1995) and Menning et al., (2000) and official IUGS time scale is used as a reference.

CHAPTER 6

CONCLUSION

The investigated part of the Ringkøbing-Fyn High is bounded by the Horn Graben in the East and the Central Graben in the West. The study can be summarized as:

- The Ringkøbing-Fyn High is characterized by shallow basement rocks which comprises ESE- WNW to E-W to ENE- WSW to NE- SE trending tilted half grabens.
- Major rifting in the area took place in the early Permian based on the stratigraphic dating method and most of the faults are restricted below the late Permian Zechstein Group.
- However, extensional faults older than Permian rifting phase have also been observed which are restricted to the southwestern part of the Ringkøbing-Fyn High. Their precise age is unknown due to lack of well control.
- At the early Permian level, geometry of the normal faults varies from planar to slightly curved to listric.
- The study shows that the Ringkøbing-Fyn High was uplifted in the early Permian and remained uplifted until early late-Triassic based on the seismic interpretation results. It is supported by the evidence of finding a thin succession of the late Triassic at places over the high.
- The Skagerrak Centered Large Igneous Province (SCLIP) derived from the Core Mantle Boundary might have been the reason for the uplift of the Ringkøbing-Fyn High based on its chronological similarity with stratigraphic dating of the faults found in the study area.
- The effect of the Variscan compression further to the south can not be neglected but seismic interpretation is unable to find any such evidence.
- Thick late Permian and Triassic succession in the adjacent Norwegian-Danish Basin shows that the basin has experienced enough subsidence due to overburden during these time intervals.
- The southern part of the Ringkøbing-Fyn High experienced more uplift as compared to the northern fraction as a result the Palaeozoic succession preserved in the half grabens is much thicker in the northern sector, approximately 1500 ms (twt) as compared to the southern part (up to 450 twt).
- Over the Ringkøbing-Fyn High and adjacent Nowegian-Danish Basin, the interpreted Palaeozoic succession is analogous to Skagerrak Graben preserved in the tilted half grabens.
- Some of the Permian faults have been reactivated in the Triassic and the mid-late Cretaceous. The reactivation of the faults in Triassic is concentrated in the proximity of the Horn Graben which might had reactivated during rifting of the Horn Graben.

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