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Abstract

Detailed examination of well-constrained three-dimensional seismic data introduces the role of tectonics in controlling the nature of syn-rift sequences on the hanging wall of faulted blocks, typical Late Jurassic structural traps in Northern North Sea at all and Gullfaks field in particular. Facies architecture, thickness variations and the internal character of the Brent Group allows to evaluate the syn-rift nature of deposition with strong influence of sub-basin geometry. Significant variations in displacement (throw) along the fault length exhibit characteristics of interplay between tectonics, sedimentation and relative sea level change. Fault displacement analysis combined with detailed study of isopach and dip maps for each of the key formations of the Brent Group show the results with far-reaching consequences for existence additional stratigraphic traps attractive for development drilling.

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Introduction

Due to rapid development of oil industry in recent years the integrated study of both tectonics and sedimentation reached a significant progress even on petroleum system scale. Since many geological problems could be considered as a result of action of tectonic and sedimentary forces an author would like to emphasize in this thesis project on particular problem in structural geology. i.e. how does the tectonics contribute to the deposition of particular geological feature. In other words the main purpose of this paper is to examine the behavior of faulted blocks in Gullfaks field, Northern North Sea, by detailed seismic interpretation and analyzing of variety diagrams related to fault dimensions and displacement.

The purpose of this study is finding evidence for tectonic control deposition of Brent Group within Gullfaks oilfield, Northern North Sea.

The main objectives are:

- to investigate relations between subsidence and sedimentation patterns within Upper Ness Formation, Brent Group;
- to propose possible approach in tectonic influence on sedimentation within Brent Group;
- to investigate and establish the significance of syn-rift deposition on both East Shetland Basin and probable petroleum system within Upper Ness Formation scales

These objectives could be achieved by following steps needed to be done:

- to interpret key horizons and major faults;
- to generate structural model of the those fault blocks which may represent tectonic influence on sedimentation architecture of horizons;
- to export data into MS software in order to calculate major dimensions of faults;

- to generate fault-displacement diagrams with emphasize on throw – length analysis

1. Previous studies. Literature review.

Since the obvious significant importance of the Brent Group for both UK and Norwegian Sector on North Sea, a large number of papers been published over exploration, petroleum geology, structural evolution, sequence stratigraphy, sedimentology, hydrocarbon generation and migration. Despite the long passage of time since the original discovery was made, over 30 years ago, and despite the subsequent drilling of several hundred exploration development wells major controversies still exist, particularly over depositional environment digenetic models and tectonic influence on deposition (Statteger and Morton, 1992).

It was generally agreed in recent times that Brent Group was originally deposited during a period of active rifting and subsidence. However, Yielding et al., show quite earlier occurrence of rifting phase with Brent deposition related to thermal subsidence. A number of papers deal with sedimentological approach of evolution of the Brent group beginning with review of by Richards. Cannon et al., and Helland-Hansen et al consider new approach in interpretation of the Brent Delta as ‘deltaic’ environment by considering the Brent sequence as a prograding wave-dominated delta. Regional sequence stratigraphy of the Brent delta within Norwegian sector of northern North Sea is an issue of papers by Stattegger et al and Bjørlykke et al.(1992). Regarding tectonic influence on sedimentation within particular formations of the Brent Group Yielding proposes deposition of the Group prior to zenith of renewed rifting which occurred in the Late Jurassic (Yielding et al., 1992).

The general concept about tectonic influence on deposition of one particular stratigraphic unit is described by Dawers and Underhill (2000) on example of Statfjord East Area. Detailed focus on interplay between tectonics and sedimentation responsible for facies architecture and distribution was carried out by Ryseth (2002) pointing out differential subsidence in the Ness Formation. Despite the integrated study of both tectonics and sedimentation reached the significant progress due to rapid development of oil industry in recent years, only a few of the papers been published regarding tectonic influence on sedimentation patterns within the Brent Group in Gullfaks field. A suite of papers were dedicated by Fossen to structural evolution and fault analysis in Gullfaks filed. The major efforts were put onto structural core analysis, properties of the fault population, and sensitive analysis on probability of absence of small faults in the Gullfaks field (Hesthammer and Fossen, 2001; Fossen and Rørnes, 1996; Fossen and Heshammer, 2000).

The methodology and integrated approach of using sensitive analysis associating displacements with dimensions of the faults is given by a number of papers published by Walsh and Watterson. A suite of papers starts with general methodology of fault growth model introduced as a tool to predict relationships between width and displacement of the fault (Watterson, 1986). Factors affecting displacement gradients of a single fault are described in the next progressive paper by Walsh and Watterson (1988). The final paper an author would like to point out regarding fault dimensions relationship investigates the power law distribution of the fault size (throw) (Nicol et al., 1996).

Since the discovery of the giant Gullfaks filed in 1978 a suite of papers was carried out with major focus on Brent reservoir development. However two of those are essential in this thesis project. Petterson et al. (1992) gave the brief summary of exploration history with detailed observation of main structural elements within Gullfaks area. Tollefsen et al. (1992) dedicated the paper to the structural complexity of the field causing the chosen strategy for development with subdivision into main 2 phases. He also put stress to the potential problems for production since the sandstones of Lower Brent unit appeared to be unconsolidated.

As it might be observed above in recent times not significantly enough efforts were put on investigation of tectonic influence on deposition of the Brent Delta sediments within Gullfaks area. Consequently the thesis project and employed methodology and hypothesis should definitely contribute to a concept of syn-rift deposition with main objectives to determine implication for petroleum geology.

2. Regional settings of Gullfaks area

2.1 Location

Geographically speaking, the Gullfaks oil field is situated on the in the Norwegian Sector of the Northern North Sea along the western flank of the Viking Graben. (Fig.2.1). Gullfaks represents the shallowest structural element of the Tampen spur. The field is related to block 34/10 which is approximately 175 km northwest of Bergen and covers an area of 55 km2 and occupies the eastern half of the 10-25 km wide Gullfaks fault block (Fossen and Hesthammer, 2000). The Gullfaks field is the first license ever run by a fully Norwegian joint venture corporation consisting of StatoilHydro and Saga Petroleum (Tollefesen et al., 1992). The field produces from three separate CBS platforms, the Gullfaks A, B and C. Gullfaks A and C are fully independent processing platforms with three separation stages.

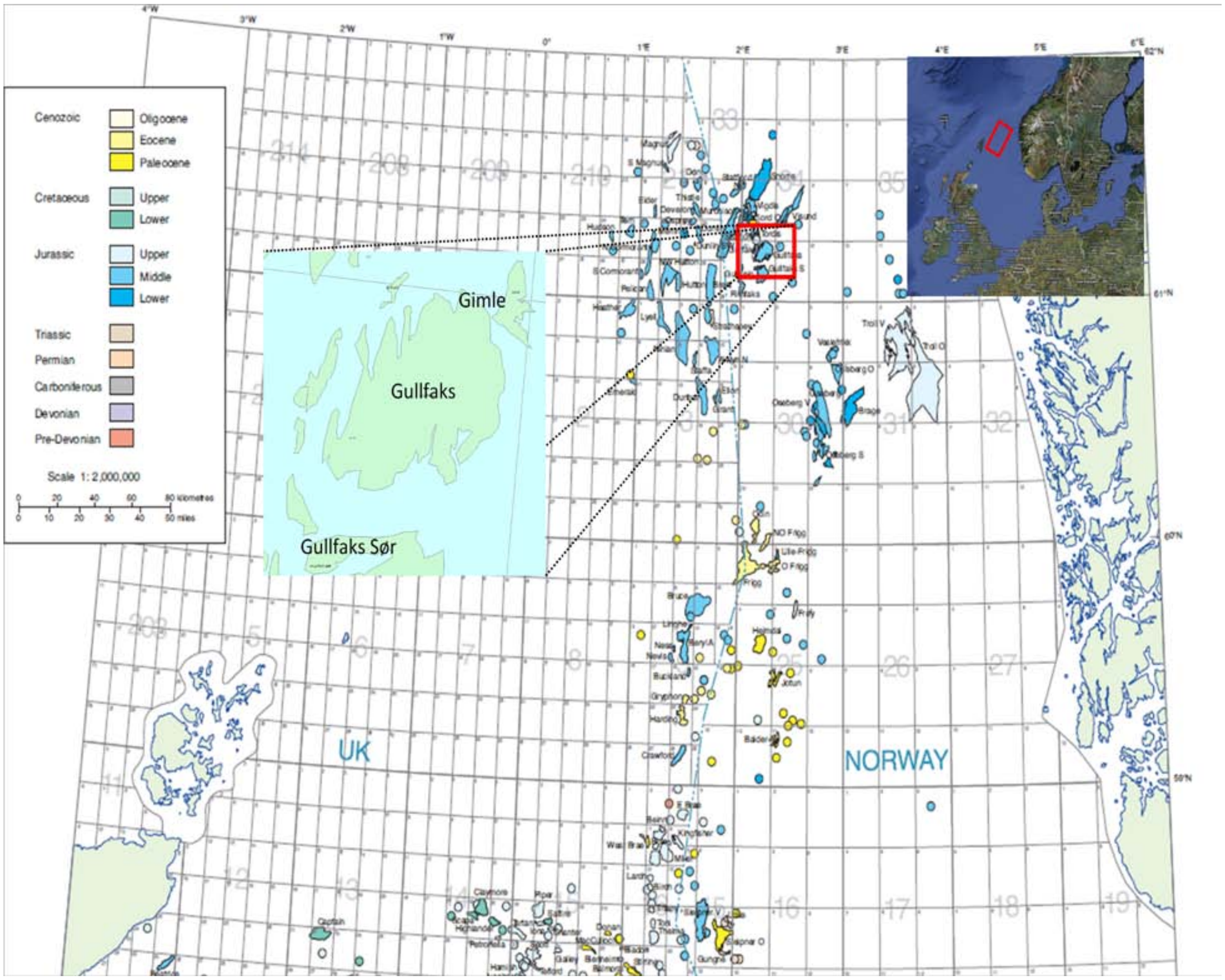


Fig.2.1 Regional position of the Northern North Sea and the study area (red square)

3. History review. Gullfaks field

3.1 Exploration history

Since the discovery of the Brent field in 1971 the Middle Jurassic Brent Group sediments became, in economic terms the most significant hydrocarbon reservoir in NW Europe. Block 34/10 was awarded to the license group in 1978 during the 4th concession round (Tollefesen et al., 1992). The first well, 34/10-1, penetrated the Jurassic section encountered about 160 m of oil-filled Brent sandstones with oil column down to the base of the Brent Group. The next four exploration wells (34/10-3, - 4, - 5, and -6) were drilled in the western part of the field and established the oil-water contact (OWC) at 1947 m MSL.

The next stage of exploration process became the use of 3-d seismic data which first time was shot over the structure in 1979. After some improvements had been made on basic data quality, together with the large increase in data quantity, mapping of prospective areas for drilling in the Eastern part of the field was performed. Well 34/10-7 proved a deeper hydrocarbon system in the Cook Formation. Next five exploration wells (37/10-8, - 9, - 11, - 13 and -14) been drilled in continuation of exploration of eastern part were all successful with proving a deep OWC and new petroleum system in the Statfjord Formation.

By the end of 1983 both exploration and production phases were completed with 14 wells had been drilled into structure. Exploration results are evaluated as follows.

1. Number of successful wells – 10
2. Number of dry wells – 3
3. Abandoned wells – 1.

To summarize exploration history of the Gullfaks field, and according to Petterson (1992) 3 exploration wells are essential in order to understand the structural positions of the main reservoirs (see figure 3.1)

1. Well 34/10-3, discovered the oil-water contact at 1947 m MSL in the Brent Group, western area;
2. Well 34/10-9 in the central area, proved hydrocarbon-bearing sediments in Cook Formation with OWC at 2090 m MSL;
3. Well 34/10-11 drilled into horst block and discovered oil-bearing Statfjord Formation

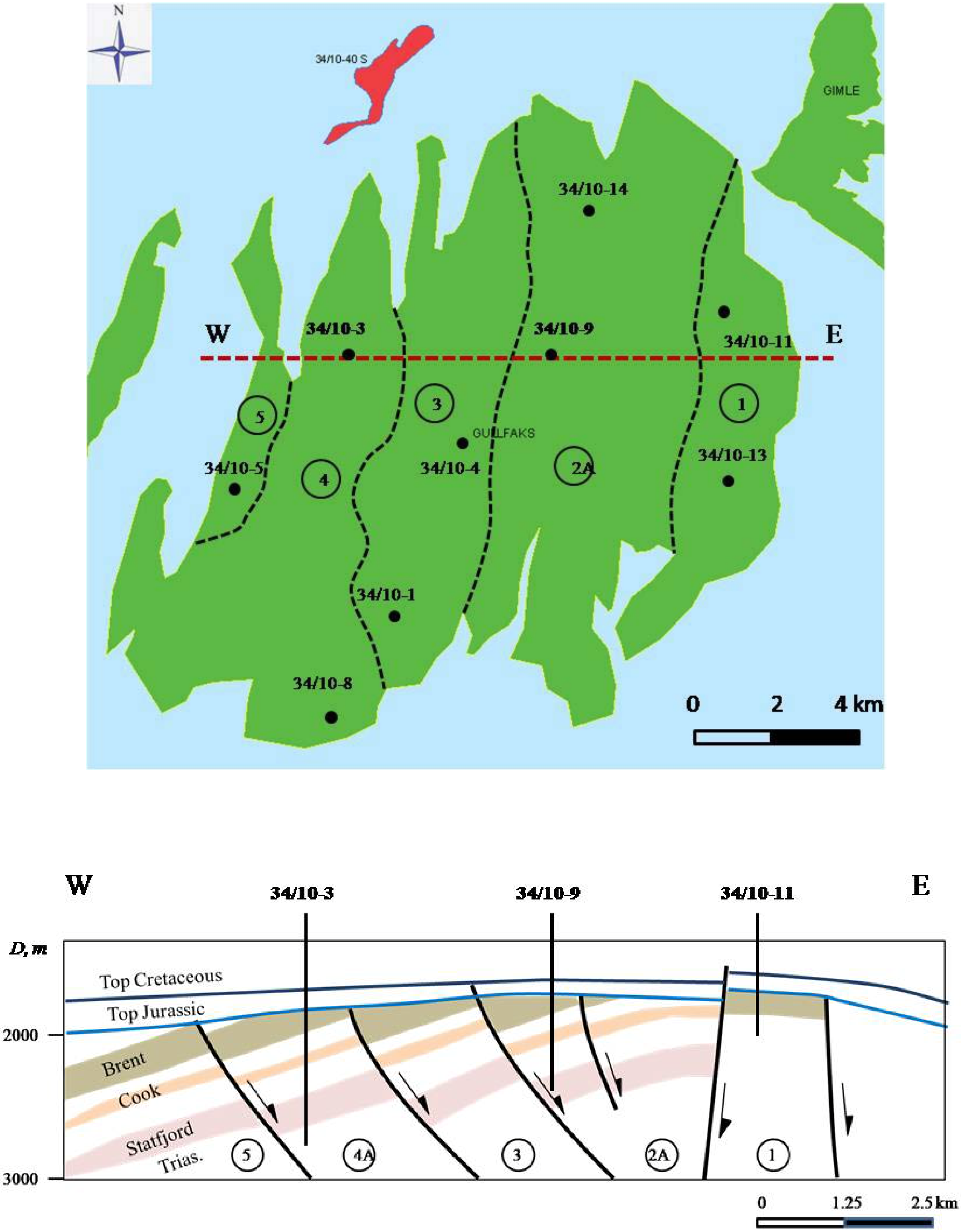


Fig.3.1 Detailed map of the Gullfaks field showing location of the exploration wells and general nomenclature of the fault blocks. Modified after Erichsen et al.,(1987), and Petrobank ® data base.

3.2 Development history

Based on interpretation of subsurface data and available core a 2 phase field development plan (FDP) was proposed. Following the Commerciality Report dated October 1980, the authorities approved the plan for primary development of the western area from Gullfaks A and B platforms with further development of the eastern part by Gullfaks C.

The development program according to Pettersen et al. (1992) described below is taken from the development plans for phase I, dated January 1986, and phase II, dated December 1984. An updated field wide development plan was completed in November 1988.

Since the following formations were considered as separate reservoirs, according to FDP those formations supposed to be developed individually until filed results proved communication with other reservoirs.

- Upper Brent (Ness and Tarbert formations);
- Lower Brent (Rannoch and Etive formations);
- Cook formation;
- Statfjord Formation.

The overall development concept was to produce the reserves successively shallower within the Brent Group with water injection as a major drive mechanism. In order to minimize potential sand problems during production selective perforation was employed. The approximate recoverable reserves at the first stage of development were estimated to 230 mil. Sm^3(Tollefsen et al., 1992).

The more complex Phase II was started with installation of Gullfaks B, a second CBS platform, in order to produce hydrocarbons from Brent, Cook and Statfjord formations. Approved by authorities the second stage of Gullfaks field development were considering a 60° deviation as a limit in drilling platform wells. The overall production strategy in Phase II was unchanged compared to the FDP in Phase I.

December 22nd, 1986 was a date Gullfaks A platform came to on stream. Gullfaks B started production in February 1988, whilst Gullfaks C came on stream in December 1989.

4. Structural development

4.1 Tectonic history

Much of tectonic framework of the entire North Sea region developed in three main convergent tectonic episodes (McKerrow et al., 2000): the Ordovican or Taconic / Grampian orogeny from about 460 to 450 Ma, the Devonian or Acadian Orogeny around 400 Ma and the Variscan / Appalachian Orogeny from 400 to 300 Ma. In NW Europe these can be divided into two separate accretionary events, the Caledonian and Variscan (Evans et al., 2003).

A general outline of the most important events in the tectonic evolution of the North Sea area might be given as follows through 8 major phases (Glennie et al., 1998). Many authors emphasize three of those as mainly related to the original tectonic organization, two – as a response to margin effects and other five events are related to intraplate deformations.

1. Precambrian events.
2. Caledonian plate cycle. Prior to these events, the North Sea area comprised widely separated continental fragments.
3. The Variscan plate cycle (From Devonian to Late Carboniferous). This event might be described by rifting as a result of adjustment between and along the margins. The Late Carboniferous Variscan Orogeny marked the closure of the supercontinent Pangaea.
4. Permo – Triassic rifting and thermal subsidence. This event significantly contributed to the formation of Central and Viking Graben. Subsequent Triassic to early Jurassic thermal subsidence was abruptly terminated by a phase of Middle Jurassic thermal doming.
5. Diffuse and transient mantle-plum head resulted in middle Jurassic domal uplift with widespread erosion of the central North Sea area consequently. This event also is characterized by active volcanism and the subsequent development of a trilete rift systems.
6. Late Jurassic to earliest Cretaceous extensional tectonics. Tilted fault blocks adjacent to the Central and Viking Graben and now representing the majority of hydrocarbon bearing formations within the North Sea

region were formed in that particular stage. The late stage of Late Jurassic extension resulted in post – rift thermal subsidence.

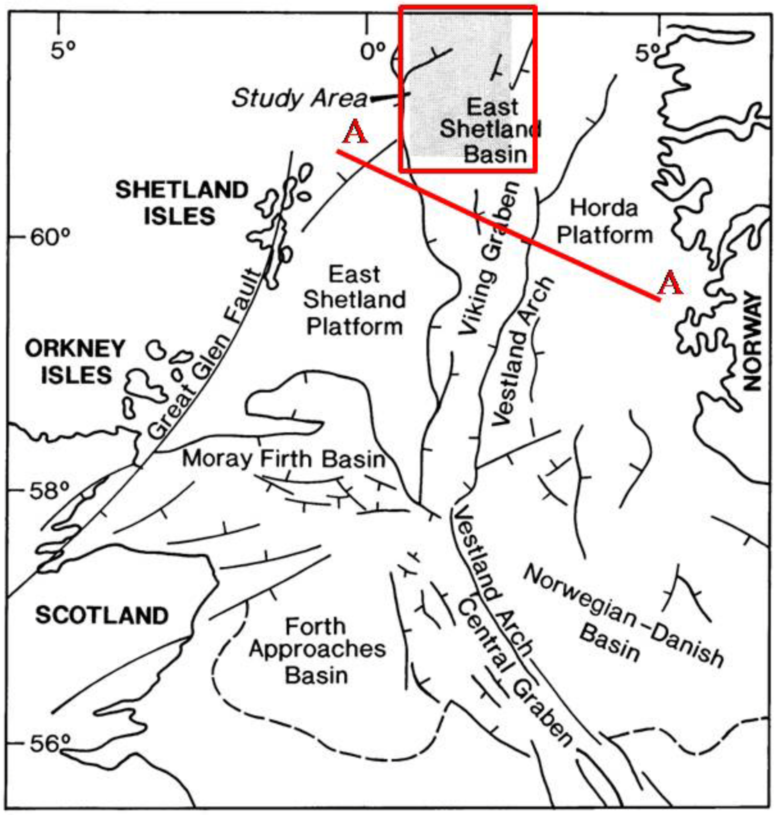
7. Opening of the Atlantic Ocean and the development of the Iceland hot spot.
8. Tectonic inversion of Mesozoic basin. Intraplate compression leaded to the tectonic inversion of former sedimentary basins across NW Europe.

Despite the main structural events listed above, it should be emphasized that the regional tectonics had further modifying effect on the tectonostratigraphic development of the area mainly through the plate tectonic control on both climatic settings and sedimentation.

The combination of time, latitude – related climatic changes, the pattern of structural deformation together with sediment supply and erosion is responsible for hydrocarbons being in sedimentary reservoirs whose ages range from Devonian to Cenozoic.

4.2 Regional structure. The East Shetland Basin.

The East Shetland Basin as a part of major North Sea Basin lies between The United Kingdom and Norway (fig. 4.2). It was formed in the Mesozoic by dominantly tensional tectonics during the break-up of Eurasia from North America (Ziegler, 1981). Brittle fracturing began in the Permian and continued well into the Cretaceous. The major graben boundary faults were reactivated in Tertiary and possibly Quaternary, although with main control in sedimentation in thermal subsidence. The East Shetland Basin is associated with Viking Graben, a relatively deep basin characterized by north-northeast to south-southwest trends. It is relatively narrow at its southern end but broadens out to a series of sub parallel tilted fault blocks and basins at its northern end. Faults oriented west-northwest-east-northeast divide the north-northeast to south-southwest trend into discrete fault blocks (Miles, 1990). The major oil fields including Gullfaks are located at the crests of these features in reservoirs of Triassic to Middle Jurassic age.



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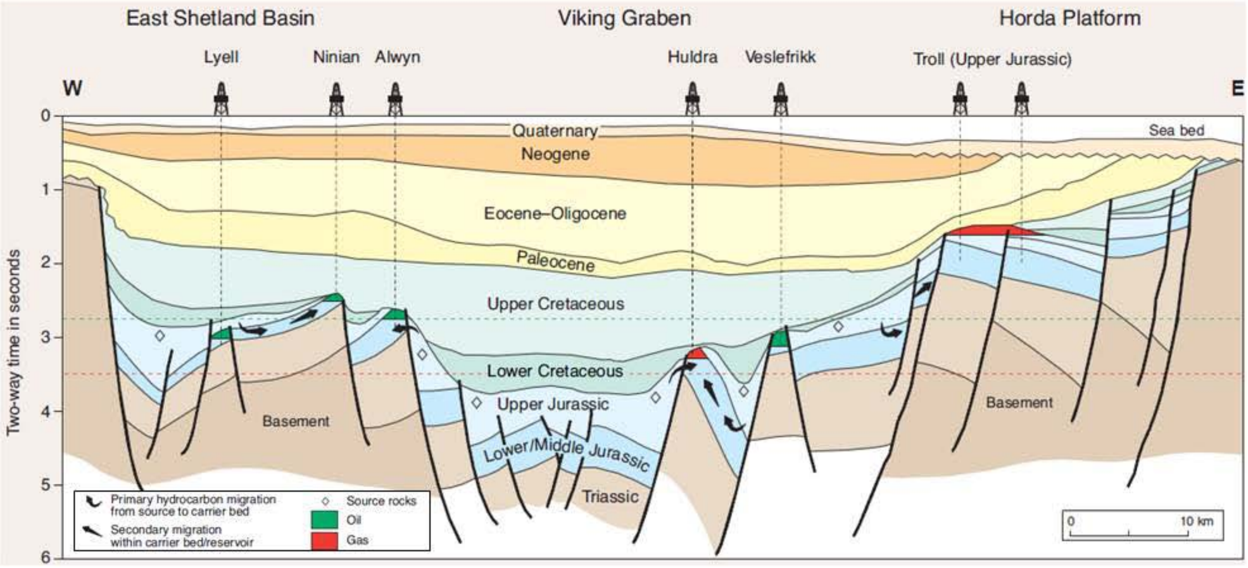


Fig.4.2 Location map. Viking Graben and East Shetland Basin. Cross-section A-A shows distribution of hydrocarbon bearing formations within the Lower Jurassic to Paleocene. Note all oilfields related to the tilted fault blocks traps. Modified after Miles(1990) and Evans et al. (2003)

4.3 Local structure. Gullfaks domino faults

Structural genesis of the Gullfaks field took place throughout the Jurassic, culminating during the Late Jurassic to Early Cretaceous in connection with regional tectonic movements in the East Shetland Basin (Pettersen et al., 1992).

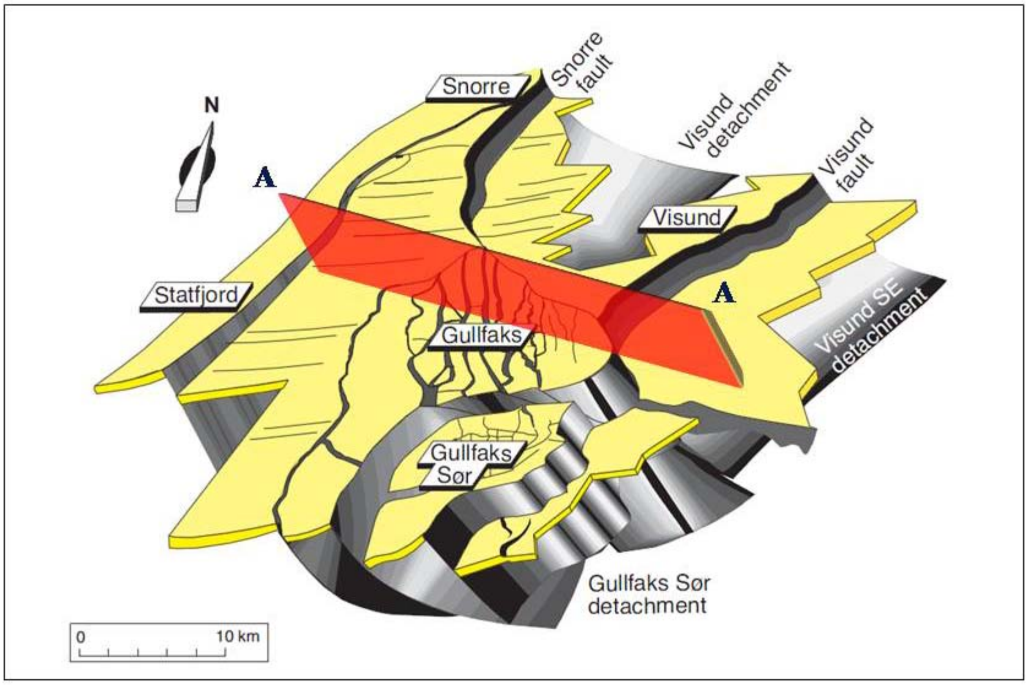
The rifting been dominated structural style appeared to have controlled the development of the Gullfaks structure resulted in subsidence with normal faulting and block rotation.

The Gullfaks fault block is one of the first-order N-S elongated fault blocks in the North Sea rift system (Fossen and Hesthammer, 2000). The fault block shows evidence of strong internal deformation mostly represented by a domino fault system with east-dipping faults and west dipping formations (fig. 4.3). Previous studies on Gullfaks field (Hesthammer and Fossen, 2001; Fossen and Rørnes, 1996) based on detailed seismic interpretation of subsurface data suggest the structural subdivision of Gullfaks field into 3 contrasting compartments: a western domino system with domino-style fault block geometry, a deeply eroded eastern horst complex of elevated subhorizontal layers and steep faults, and a transitional accommodation zone or collapsed fold structure.

The western part of Gullfaks field is presented by a series of rotated fault blocks. The normal faults, which strike in a north-south direction exhibit fault planes that dip at rather unusually low angles of approximately 30 to 40° to the east, whereas the formations dip at 10-15° to the west. There is also general decrease in dip from the footwall to the hanging wall positions (from east to west) giving rise to a gentle hanging wall syncline. That structural event had been interpreted as a large-scale drag which reaches the maximum at shallow reservoir levels (Fossen and Rørnes, 1996).

The central area defined as accommodation zone complex could be structurally described as a graben feature with poor seismic data quality causing complication of mapping minor faults. Dip values vary from approximately 10° to more subhorizontal in the eastward direction. The zone is typically defined by a collapsed anticline with west-dipping western limb and a subhorizontal to gently east-dipping eastern limb.

An almost vertical fault defines the boundary between Accommodation Zone and eastern Horst complex. This area is characterized by uplifted Statfjord formation up to 300 m relative to the central part. That particular elevation of the horst structure obviously resulted in complete erosion of the Brent and Cook groups. At the northern and southern flanks of the horst the erosion can be followed down into the Hegre Group of the Upper Triassic resulting in erosion of more than 700 m of Jurassic strata.



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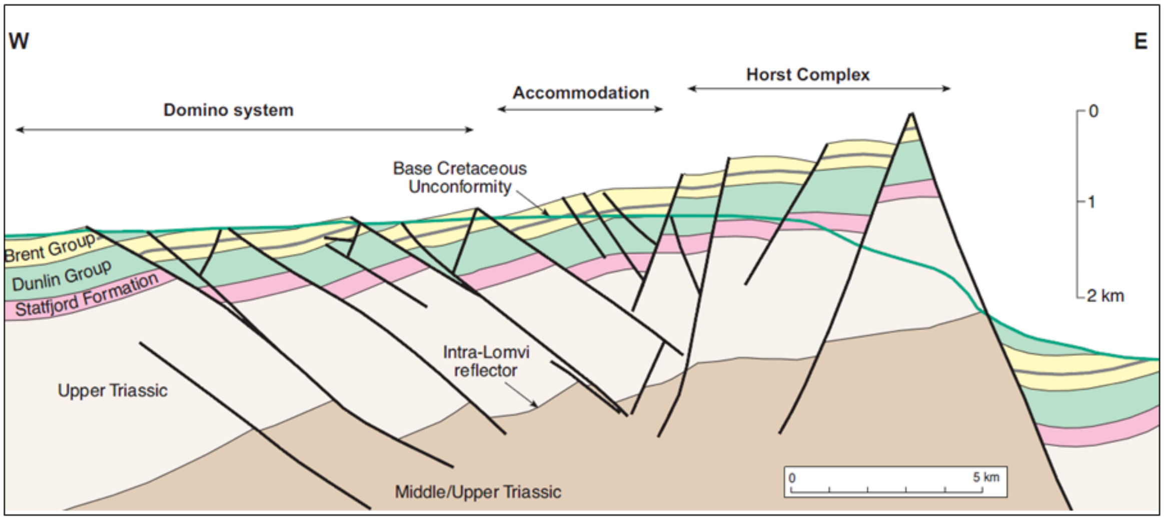


Fig.4.3 Structural complexity of the Gullfaks field with subdivision to 3 major features. Modified after Evans et al. (2003).

5. Stratigraphy and depositional environments with focus on Brent Group.

5.1 General Brent Group description.

The recoverable oil in the Gullfaks field is found primarily in three reservoir sandstones:

1. The Statfjord Formation.
2. The Cook Formation.
3. The Brent Group.

Since the major interest within the thesis is dedicated to the Brent Group the description of lower Statfjord and Cook formations is omitted.

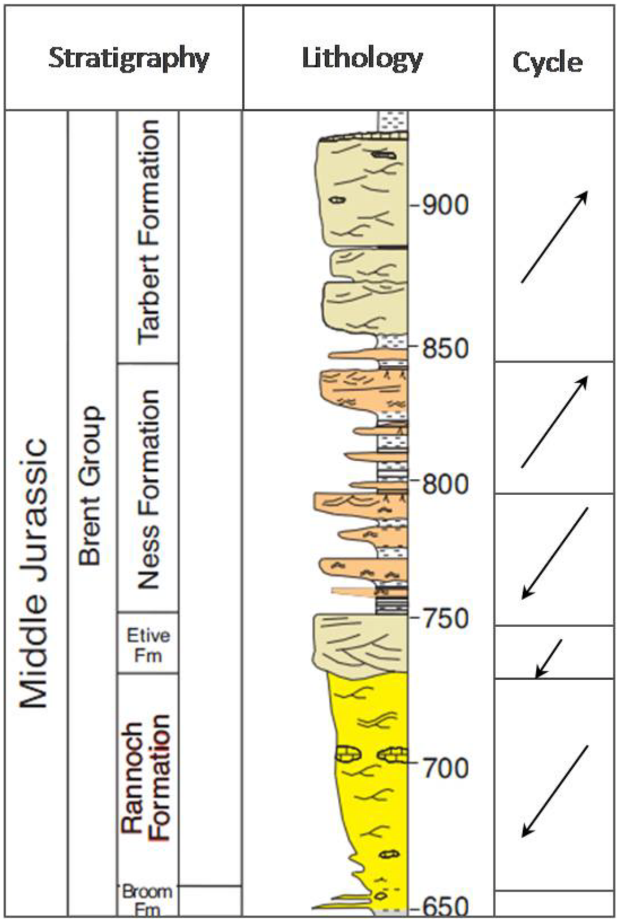


Fig.5.1 Stratigraphic column of the Brent Group. Digits represent the thickness of the column. Modified after Evans et al., 2003

It is generally agreed that Middle Jurassic deposits of the Brent Group are represented by the deltaic sediments with deposition strongly controlled by regressive/transgressive cycles and occurred during the late phase of post-rift subsidence following the Late Permian/Early Triassic rifting (Ryseth, 2000). The thickness distribution is consequently controlled by both the thermally driven subsidence and ongoing faulting of the Late Jurassic-Early Cretaceous episode of rifting.

Basically the Brent group is subdivided into 5 major stratigraphic units as Broom, Rannoch, Etive, Ness and Tarbert Formations. This petroleum system is a sequence of sandstones, siltstones, shales and coals with maximum thickness of 300-400 m.(fig.5.1). The Broom and Oseberg Formations may represent early lateral infill of the basin whereas the remaining formations, containing the majority of the bulk volume of Brent Group, comprise a major regressive (Rannoch, Etive and Ness Formations) to transgressive (Ness and Tarbert Formations) clastic wedge (Helland-Hansen et al., 1992). Fig. 5.1 represents the entire Brent Group section with major transgressive/regressive cycles. As it might be observed, the change in relative sea level occurred as a transition to transgressive cycle in Ness time dividing this unit into Lower and Upper Ness.

5.2 Broom Formation

The Broom formation represent a unit formed by mudstones/shales with variation in thickness 5-15 m interbedded with thin layers of coarse sandstone and gravel beds been interpreted as deposits of marine environment. The thin sandstone beds usually are carbonate cemented and in restricted communication with the overlying sandstones of the Rannoch Formation.

5.3 Rannoch Formation

The Rannoch Formation generally regarded as delta front shoreface might be subdivided into three main units Rannoch-1, Rannoch-2, and Rannoch-3. The Rannoch formation may comprise an overall upward-coarsening sequence in a sheet formed sandstone body that thins to the south with thickness variety of 50-90 m.

5.4 Etive Formation

Etive formation according to recent studies was interpreted as a barrier bar complex. On the basis of low-angle large scale cross-stratification, grain size, heavy mineral concentration and parallel lamination a high energy beach environment was proposed (Petterson et al., 1992). Formation consisting primarily of medium-to coarse-grained sandstones varies in thickness of 15 to 40 m with lower part reflecting upward-fining sequences that may represent channel fill deposits. These sequences are interpreted as tidal inlets in the barrier bar system.

5.5 Ness Formation

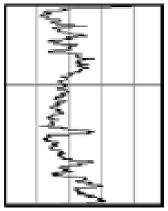
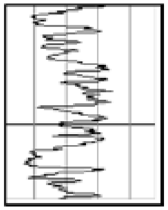
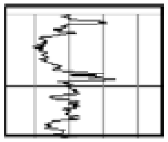
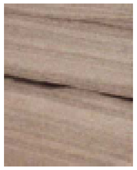
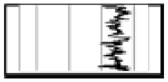
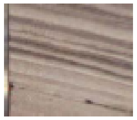
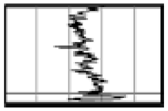
The Ness Formation being a primary target of thesis project should be highlighted in more details comparing to others oil-bearing formations within the Brent Group. Basically, the boundary between Etive and Ness Formation is assigned by the first occurrence of a coal bed above the clean sands (Tollefsen et al., 1992). A delta plain suggested for the unit. Despite the regular subdivision of Ness formation into 3 units, Ness-1, Ness -2, and Ness-3 according to well logs and core data, an author prefers use another nomenclature and subdivision. Since a number of publications (Yielding et al., 1992; Cannon et al., 1992; Helland-Hansen et al., 1992) suggest the turn to the transgression cycle in particular Ness time, it might be geologically valuable to divide Ness Formation into two parts, Upper Ness and Lower Ness with relative sea level change as the main criterion of subdivision. So the lower unit interpreted as low-sinuosity distributary channels consists of interbedded coals, mudstones, and sandstones, occasionally with thick sandstone channel deposits. Additionally several coarsening-upward sequences of sandstone with good reservoir quality propose the crevasse splay, crevasse channels and overbank flooding. The Upper Ness unit might be described as domination of silistone/claystone and coal deposits with some lacustrine deposits.

5.6 Tarbert Formation

There is controversy exists regarding the boundary between Ness and Tarbert Formation and depositional environment consequently. The group of authors mainly Pettersen et al. (1992) distinguish the boundary between those formations as marine transgressive event that separates these two different phases of delta building. Alternatively, Yielding et al. (1992), Graue et al. (1987) propose that marine transgressive event prior to Tarbert deposition in Ness time. Since the previous research that had been done on earlier stages of the thesis project, an author confines the assumption of earlier transgressive event, in particular Ness time being responsible for sedimentation patterns within the Upper Ness. Consequently from that point of view the Tarbert formation is interpreted as pure controlled by the marine environment. Lithology varies from shales, siltstones and coal beds to medium-to coarse-gained sands in which calcite cementation is found.

Based on review of the available well logs some of the common GR response were analyzed in order to perform the Table 1 listed below.

Table 1. Interpretation of depositional environments of the Brent Group

Age	MS	Formation	Common GR response	Lithology	Depositional environment	Core photo
Bajocian	**J32**	**Tarbert**		Grey to brown relatively massive fine to medium grained sandstone with subordinate thin siltstone shale and coal beds	Marginal marine, reworked delta plain deposits in the onset of the marine transgression	
	J24	**Ness**		Association of coals, shales, siltstones and very fine to medium grained sandstones. The shales are silty, fissile and frequently pyritic.	Domination of coal – bearing, foodplain deposits with isolated fluvial sandstone.	
		Etive		Grey to yellowish – brown and dark brown (oil stained), moderately to poorly sotred, medium – to coarse grained sandstones	Wave-dominated delta front to strandplain, with coast parallel subaqueous sheet sands	
		Rannoch		Pale to medium grey and light brown (partly oil stained), well – to very – well sorted micaseous sandstones	Wave/storm-dominated lower – middle shoreface or delta – front environment	
Aalenian	**J22**	**Broom**		Pale grey to brown, coarse-grained poorly sorted conglomeratic sandstone containing shale clasts	Fluvial components in an otherwise marine – dominated association of facies	

6. Data and Methodology

6.1 Data

There are several seismic surveys of different types and year of acquisition within the Gullfaks field area (Table 2). According to location and volume and quality of data, it was agreed to load from Petrobank ® one particular 3D seismic data called ST8511and acquired in 1992. Figure 6.1shows the study area with chosen dataset that is actually covering the major Gullfaks field with northern part of Gullfaks Sør field.

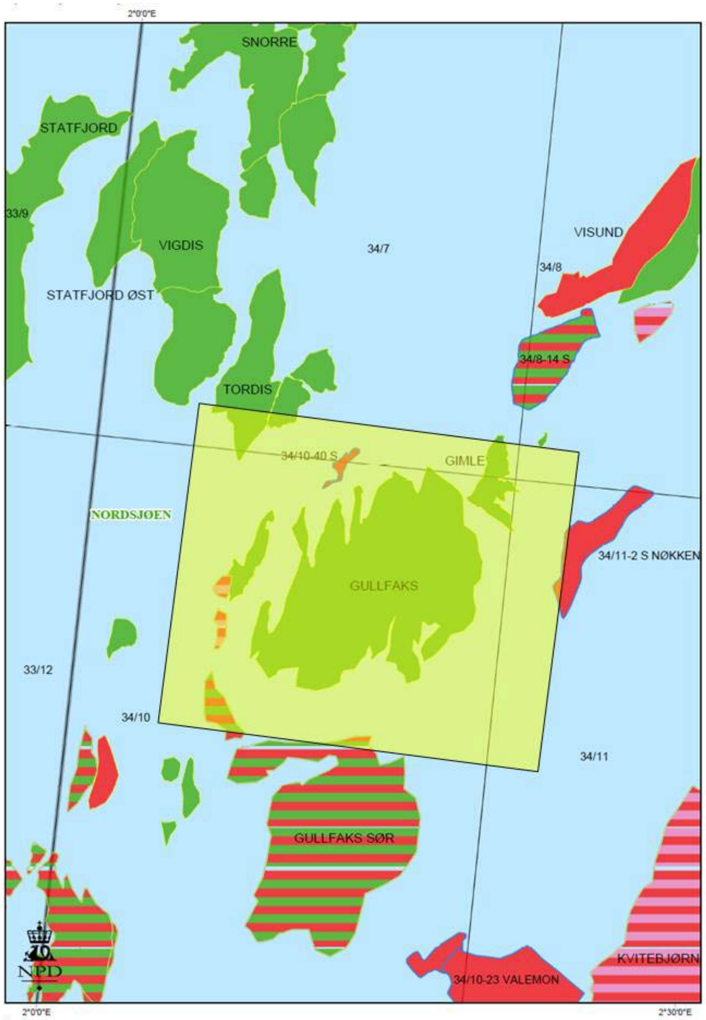


Fig. 6.1 Location of used in project seismic data set. Note that data covers not only main Gullfaks field but also represent partly Gullfaks Sør and Nøken Fields

According to recent studies within Gullfaks field (Hesthammer and Fossen, 2001) 162 wells including 22 exploration wells had been drilled on Gullfaks since the discovery in 1978. Unfortunately, only a few have proper coring program and composite logs to be useful for study. Table 3 represents the well data employed for the project. Since the quality of well logs appeared to be satisfied, please note that most of the data from development wellbores were taken from Gullfaks Teaching Project available at the University of Stavanger. However, those wellbores represent only a basic suite of well logs such GR, Porosity, Permeability, and Net Gross that might contribute to the seismic interpretation but could not be used for generation of synthetic seismograms in order to tie well log data. This is the reason of loading from Petrobank some additional preferably exploration wellbores with proper well log data including sonic and density logs.

Well logs data together with synthetics was used in order to extract geophysical properties of the reflector and to correlate logs with seismic character.

The study was carried out by using a number of software packages as Schlumberge's Petrel , Landmark's Seisworks and Geoprobe as well as MO Excel.

The detailed interpretation of seismic data together with structural geological modeling was performed by using Seismic to Simulation Petrel ® software. Landmark's packages OpenWorks and Geoprobe were employed in order to generate synthetics seismograms and visualize data. The most essential part of the project was carried out by MS Excel where sensitive analysis of fault displacement diagrams was designed.

Table 2. Available 3-d seismic surveys

Survey Name	Seismic Project	Proc Type	Proc Date	Sections
CTM94	CTM94	STK RAW	1994-01-01	2479
ST8511	**ST8511R92**	**STK RAW**	**1992-02-01**	**550**
ST9207	ST9207	STK RAW	1992-01-01	3128
ST9607	ST9607	MIG FIN	1997-01-01	2600
ST98M1	ST98M1	MIG FIN	1998-01-01	2889
ST98M5	ST98M5	MIG FIN	1999-03-16	34326
ST9901	ST9901-INTER-OFFSET-CUBE-STACK-1-8	MIG RAW	1999-09-25	1191
ST99M06	ST99M06-PSDM-TIME	MIG FIN	2000-01-28	1355
TFE-91	TFE-91	MIG FIN	1992-01-01	1715

Table 3. Wells used in project evolution

Name	Surface X	Surface Y	TVD	MD	Max incl	Well path	GR	Sonic	Density
34/10 - C4	454640	6786211	2298	2564	68.88	Y	Y	N	N
34/10 - C5	453504	6783002	2306	2337	46.45	Y	Y	N	N
34/10 - C6	451504	6781788	2425	2437	33.61	Y	Y	N	N
34/10-C9	461016	6787096	2130	3520	67.6	Y	Y	N	N
34/10-1	457626	6783217	2435	2460	0	N	Y	Y	Y
34/10-14	460014	6789182	2622	2647	0	N	Y	Y	Y
34/10-3	456946	6787020	2783	2808	0	N	Y	Y	Y
34/10-5	455546	6784438	2755	2870	0	N	Y	Y	Y
34/10-8	457008	6781760	2189	2214	0	N	Y	Y	Y

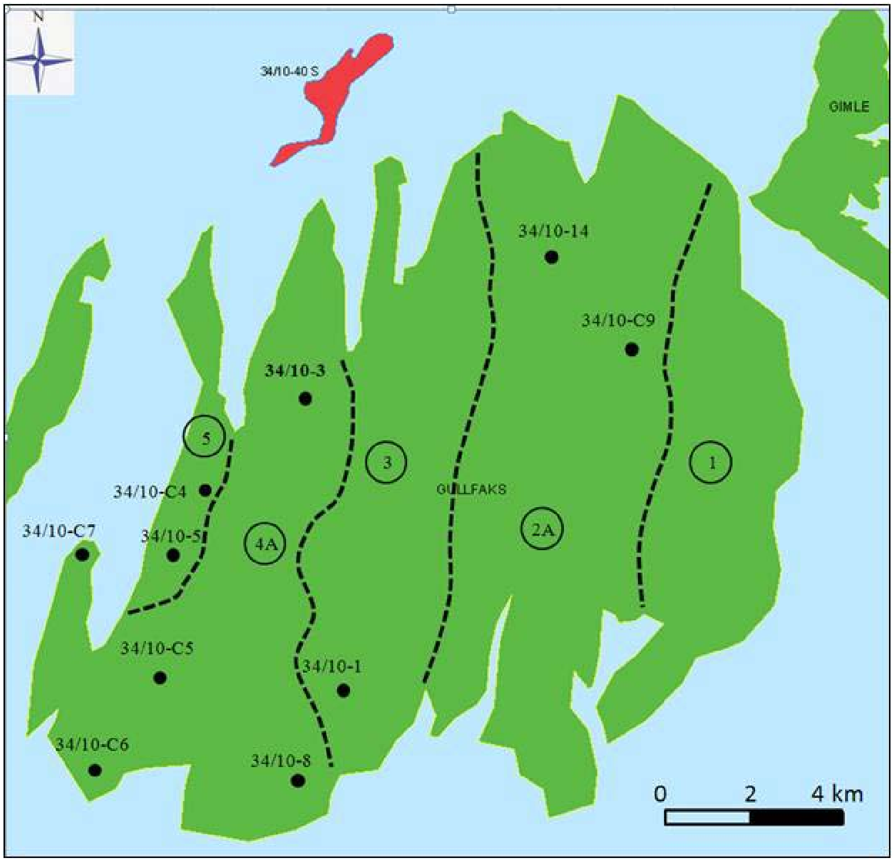


Fig.6.1.2 Placement of the chosen for the project wells. Gullfaks field with field development nomenclature.

6.2 Hypothesis

Helland-Hansen et al. (1994) suggested that biostratigraphical analysis shows that was main Brent Delta progradation was relatively rapid and occurred during the Late Aalenian to early Bajocian that slightly corresponds to deposition of lower part of Brent Group, essentially Broom, Rannoch and lower part of Ness formations. During this age the thickness of strata could be considered primarily as a result of bathymetry accommodation and subsidence pattern which was principally controlled by post-rift thermal relaxation (Helland-Hansen et al., 1994). Towards the end of this time interval some fault-related thickening/thinning patterns were beginning to manifest themselves in the far north between individual terraces of the East Shetland Basin. Similar tectonics caused the impact on thickness distribution of the Ness formation within Viking Graben and hence from this stage simultaneous activity of both tectonics and sedimentation started to influence the thickness patterns in the Brent. On a smaller scale, the Gullfaks area with surroundings, available seismic data set suggests the same influence of tectonic into sedimentation, particularly responsible for distribution of Ness strata thickness.

As it was stated above, the Ness formation could be divided into lower and upper units with major difference in coal content and sand distribution. The lower part is formed by basal fluvial channel complex covered by coal-bearing, fine grained deposits whilst the upper part of Ness formation is relatively sandy but is capped with coal-bearing, fine-grained deposits (Ryseth, 2000). Sedimentary structures include dm- size, cross-stratification of both planar and trough types, planar parallel lamination and unidirectional ripple cross – lamination (Ryseth and Fjellbirkeland, 1995). Although detailed analysis and number of articles (Ryseth, 2000; Yeilding et al., 1992; Ryseth et al., 1998)been published regarding structural architecture and depositional models of Ness formation, this thesis project is focused on investigation of structural behavior of *4A* fault block within Gullfaks field which, from author's point of view caused final distribution of thickness of Upper Ness Formation.

Available seismic data set denotes significant variations in thickness of the Ness formation in neighboring fault-bounded blocks, apparently attributable to syn-depositional differential subsidence as it shown in figure 6.2.1

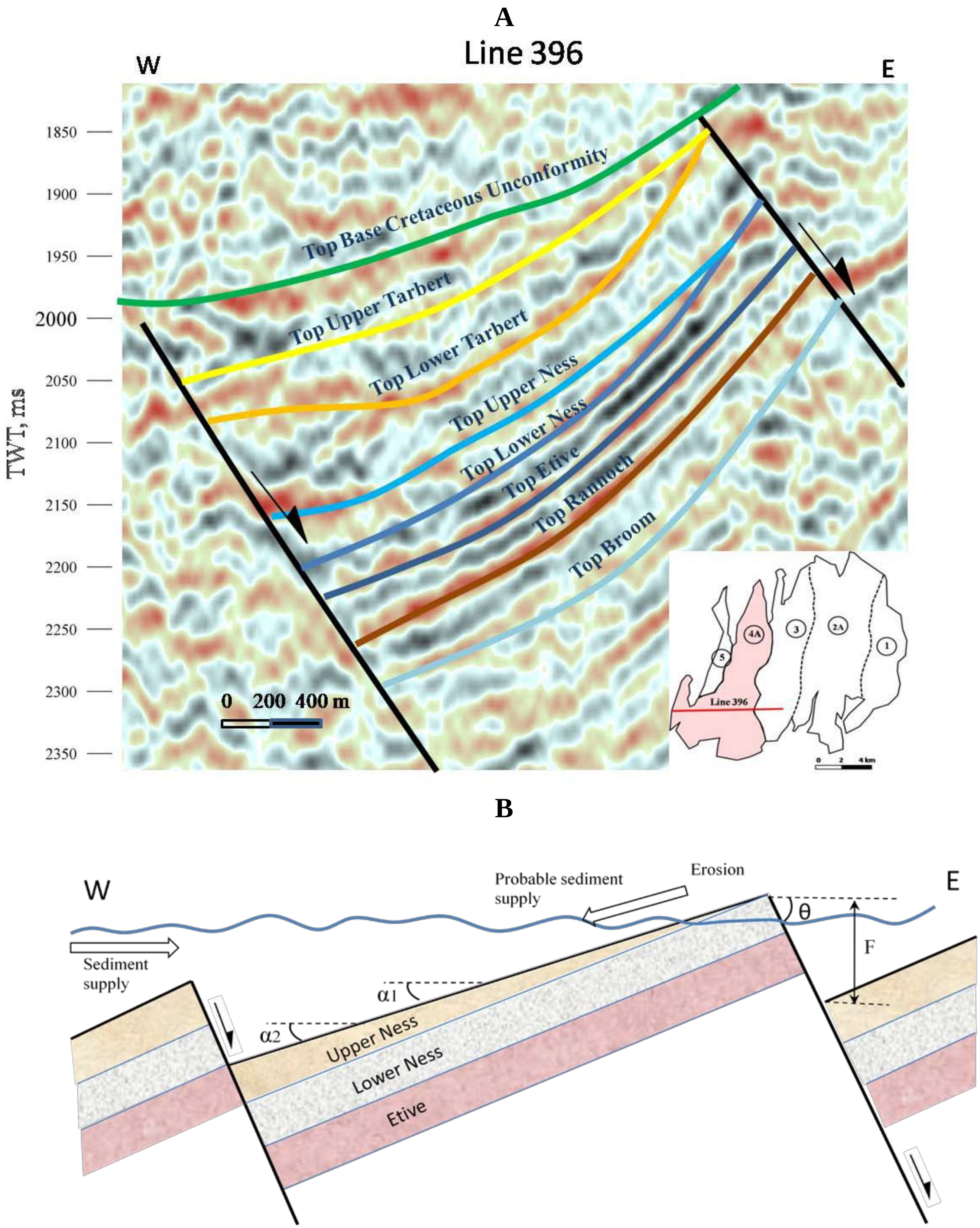


Fig.6.2.1 Suggested scenario for syn-rift deposition of the Upper Ness Formation. A shows seismic line 396 with its location. B represents the proposed model for deposition of Upper Ness

It is of great importance to emphasize on the timing of syn-rift deposition related to existence of paleo-island that from an author's point of view had been exposed to the surface in particular Upper Ness time. In other words, the detailed analysis of 3d seismic data set, seismic lines in particular, suggests the differential distribution of the thickness within the Upper Ness formation bounded by the seismic lines 396 and 361. To compare two different scenarios of the deposition of the Upper Ness the fig. 6.2.2 is further given. As it might be observed from fig. 6.2.1, the Upper Ness formation is thinning towards the crest of *4A* fault blocks with complete erosion (non deposition) on the crest leading to partly exposure the Lower Ness under the sea level. Since the superimposed strata as Lower and Upper Tarbert have the same parallel to Lower Ness, Etive, and Rannoch character of deposition, the existence of the paleo-island might be related to deposition of non parallel with relation to others Upper Ness time.

In more details, analysis of seismic data together with separation of two possible stratigraphic sequences additionally releases two possible scenarios for deposition of whole Ness Formations within Gullfaks area.

The first scenario (fig. 6.2.1) suggests the local uplift within the Gullfaks area in the beginning of Late Bajocian causing transition to the transgressive cycles and hence deposition of retrogrdational clastic wedges (Helland-Hansen, 1994) and occurred to be thinned towards the east. Note the dip angle change (alpha 1 and alpha 2) in Lower Ness as well as thinning towards the east. The model also proposes an additional sediment supply into accommodation space by the sediments from products of erosion of the uplifted part of the fault block. Throw (F) is expected to be bigger in comparison with sea level rise scenario. Theta represents the dip of the fault.

The second scenario (fig. 6.2.2) proposes relatively high sea level controlling bedding of the Upper Ness causing deposition of parallel strata to those below primarily Lower Ness and Etive.

Significant difference in those scenarios from structural point of view could be observed as existence of paleo-island in exact locations within given data set. That assumption may be supported by the detailed analysis of throw-length diagrams showing rapid change (increase/decrease) in throw values even within relatively short distance of faults.

In other words those exact crests of faulted block which were exposed to the surface during the beginning of Late Bajocian, should have relatively high values of throw in comparison with rest of the faulted block. In terms of the fault – displacement diagram the author is expecting the significant change in curve of the throw-length of the fault cross plot.

Since obvious difference in dip values between Upper Ness and Lower Ness occurs, additional evidence for tectonic influence on deposition of Upper Ness could be reached from analyzing of dip maps and particularly isopaches maps of Upper Ness. Consequently, due to thinning towards the east expected thickness of the Upper Ness on the crest of faulted block should be the minimum or almost zero.

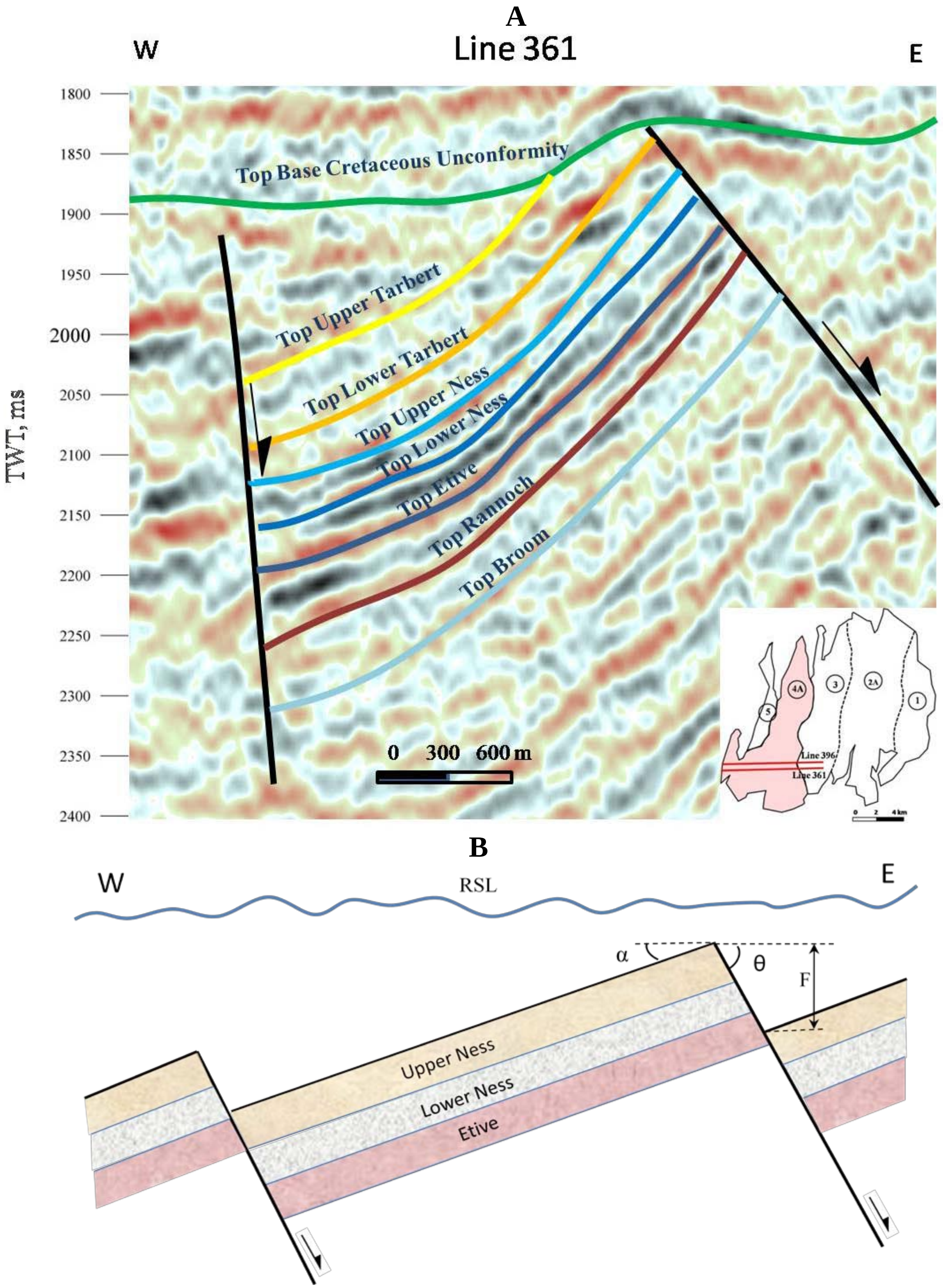


Fig.6.2.2 Deposition of the Upper Ness Fm controlled by subsidence and high relative sea level. A represents the interpretation of seismic line 361. B shows the proposed model for deposition of Upper Ness

7.Fault analysis

7.1 Basic definitions and the theory review

First of all from an author point view it is of great importance to have a short summary of general classic theory in structural geology regarding faults and fault dimensions. Please note since this particular master thesis project is considering extensional geological settings from Norwegian Continental shelf, the major efforts were put on analyzing normal faults. Correspondingly, reverse and strike slip faults are not an issue of the general theory review.

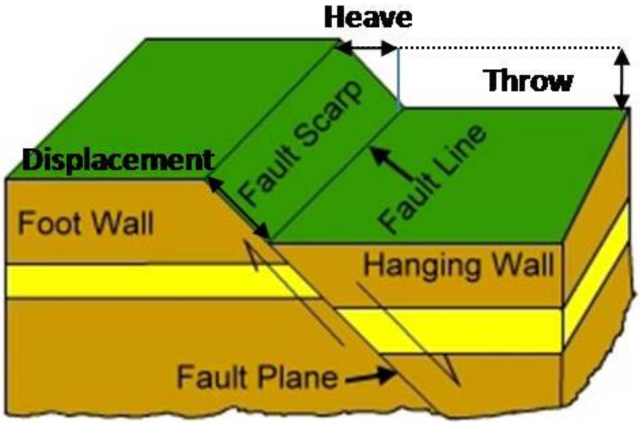


Fig.7.1.1 Normal fault and its dimensions. Modified after Ritter, 2007

Basically, to be able to perform a study some of the key definitions and concepts should be expressed as follows with schematical drawing on fig.7.1.1

Fault – a break of planar surface in brittle rock across which there is observable displacement.

Fault Displacement – the offset of segments or points that were once continuous or adjacent. Layers of rock that have been moved by the action of faults show displacement on either side of the fault surface.

Throw – vertical component of fault displacement.

Heave – horizontal component of fault displacement.

Fault Displacement Diagram – a plot showing distribution of fault displacement (heave, throw) with respect to the length of the fault.

The study is focused primarily on analyzing fault displacement diagrams with heaves and throws as a function of length of the fault. General distribution of

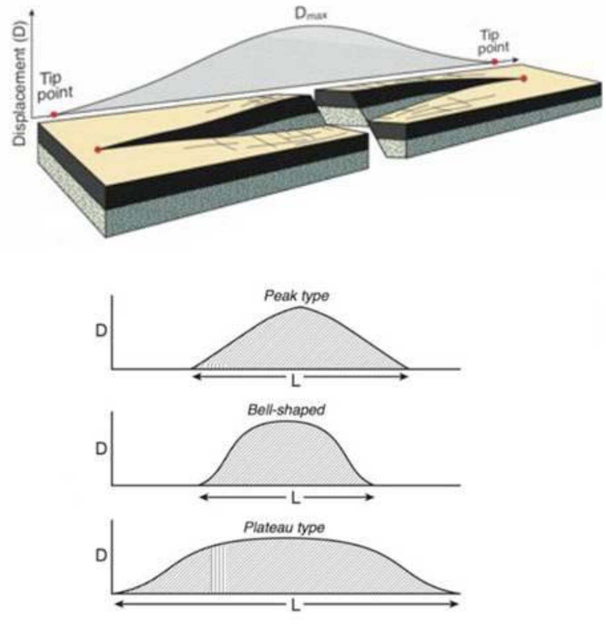


Fig.7.1.2 Fault displacement diagram.

fault dimensions along the fault length is shown on fig.7.1.2.

Basically, the project might be included in the list of studies dedicated to analysis of normal faults. The evolution of normal faults has received considerable attention over the last few years as research from several areas has converged (Morley and Wonganan, 2002). Extensive studies of fault populations have tried to establish rules governing basic faults dimensions such as fault length versus displacement and fault displacement versus number of faults of a particular size in a population (e.g., Muraoka and Kamata, 1983; Barnett et al., 1987; Walsh and Watterson, 1988, Marett and Allmendinger, 1991).

Generally speaking, displacement on a single fault surface ideally decreases to zero in all directions from a point of maximum displacement, except where the fault intersects a free surface or where displacement is transferred to a splay or to an intersecting fault (Fig 7.1.2.) In the simplest cases the fault surface is an ellipse bounded by the zero displacement contour or tip-line loop (Rippon, 1985; Barnett et al., 1987). The size of a fault trace on a map can always be referred to as the length of the fault trace because it is two dimensional. The radius of a Fault is half of either the width or the length: as most of the available data is for fault widths, the term radius here refers to half of the width, unless stated otherwise. Displacement refers to the displacement accumulated through the active life of the fault and slip refers to slip occurring during single seismic event or cycle. The displacement gradient on a fault is a measure of the rate at which displacement changes along the fault plane in a specified direction. A knowledge of the usual range of gradients can be used either for testing the geometric compatibility of a fault interpretation or for extrapolation a fault beyond the area for which data are available.

7.2 Fault analysis approach

The detailed analysis of fault displacement diagrams in the project is based on applying simple trigonometry in both 2D and 3D coordinate systems. Basically, those faults which are going to be investigated regarding sedimentation – tectonic relationships can easily be converted into fault- horizon lines or fault polygons The first scenario, however, does not allow to extract consistent point-to-point correspondence. At the same time the closed fault polygons representing by itself upthrow and downthrow as it shown in fig. 7.2.1. conclude to some manual editing of the ends. General procedure for each of the interpreted in the project faults is characterized as follows.

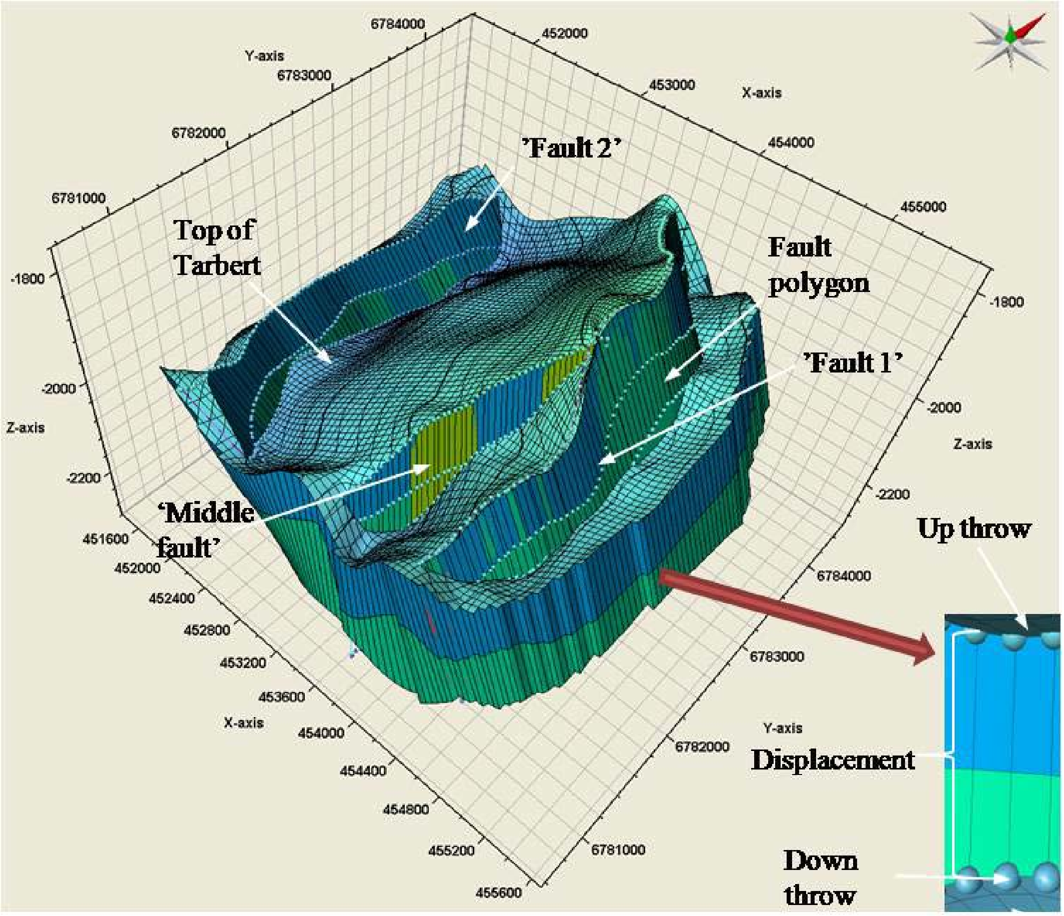


Fig.7.2.1.The structural model of 4A fault block from Gullfaks field showing applied nomenclature.

1. Interpretation by picking up each 5-th seismic line.
2. Conversion into the structural model by using increment of 200.
3. Conversion of faults into closed fault polygons.
4. Manual editing of ends of the fault polygons.
5. Export of the edited fault polygons into MS Excel.
6. Calculation of fault dimensions by applying planar geometry.
7. Design of fault-displacement diagrams with emphasizing on throw-length of the fault relationships.

At this stage of the thesis project the author would like to emphasize particularly on extraction of fault dimensions from structural model designed in Petrel.

In simplified form each fault polygon might be represented by limited surface with boundaries formed by up throw, down throw and the closest grid lines (Fig.7.2.1.). In other words, fault polygon in 3 dimensional space is subdivided into a fixed number of segments that is usually characterized by 4 points representing X,Y, and Z coordinates each. Additionally it might be significant to introduce another 2 points for each of the segment in order to be able to calculate the actual length of a segment. The chosen methodology is shown in fig. 7.2.2.

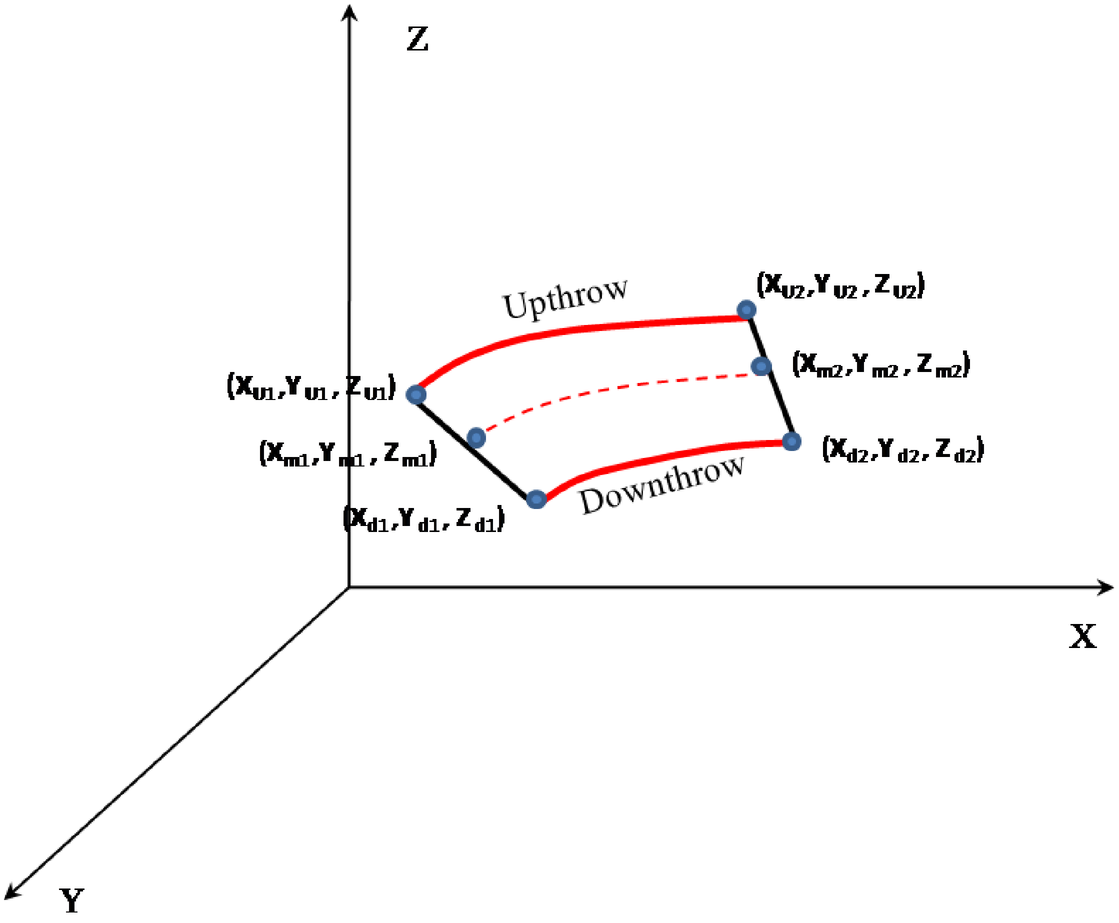


Fig.7.2.2. Fault polygon represented by 6 points with 3 correspondent coordinates. Subscription for each of the coordinate is chosen as follows. U – up throw; D – down throw; M – middle point, 1,2 – order number.

Next step in evolution of the project will be the calculation of basic fault dimensions such heave, throw, displacement and length. By taking into account planar geometry with main assumption that objective arithmetical length of the fault might be presented as a projection of middle line into XY plane, following formulas will be inserted into Excel.

1. Generally speaking heave of the fault does truly represent the displacement of the fault on XY plane. Consequently it is calculated by using following expression

$$Heave = \sqrt{(Y_{d1} - Y_{u1})^2 + (X_{d1} - X_{u1})^2}$$

2. Throw of the fault by being vertical displacement might be simply estimated as a difference in Z coordinates of one particular grid line. In other words

$$Throw = Z_{d1} - Z_{u1}$$

3. Displacement of the fault could be evaluated as the length of the straight line between two points in space. Consequently

$$Displacement = \sqrt{(Z_{d1} - Z_{u1})^2 + (Y_{d1} - Y_{u1})^2 + (X_{d1} - X_{u1})^2}$$

4. Correspondent coordinates of the middle point are easily found as arithmetical average of down throw and up throw coordinates and

$$X_{m1} = \frac{X_{u1} - X_{d1}}{2}, \quad Y_{m1} = \frac{Y_{u1} - Y_{d1}}{2}, \quad Z_{m1} = \frac{Z_{u1} - Z_{d1}}{2}$$

5. By summarizing all previous operations the arithmetical average length of the segment is expressed as

$$Length = \sqrt{(X_{m1} - X_{m2})^2 + (Y_{m1} - Y_{m2})^2}$$

7.3 Quality control of length of the fault calculations

Generally speaking, the size of a fault can be specified by its surface area, but to represent fault shape and in 2-D studies measures of the fault length commonly used (Young-Seog et al., 2003).The term “fault length” has not been consistently defined in the literature, and the measurement of the “length” is subject to various sampling constrains. At this stage of the project one remarkable note should be announced in order to avoid any misunderstandings. The term "Length of fault" directly corresponds to the length of each middle line calculated for each of the fault polygons representing the intersections of horizon with fault surface.

As it might be observed from fig.7.2.1 the length of particular fault varies in different horizons. Generally speaking, the calculated length of fault seems to be the most consistent for "Fault 1" representing the maximum error with range of 2.5 % in Etive FM. The minimum value of error, 1.2%, corresponds to Ness Fm. Since the essential part of the project is dedicated to detailed observation of Throw fluctuations along the length of particular 'Fault 1" in Ness FM, such insignificant error in length calculation supports the reliability of applied methods.

Difference in length of faults appeared to be the most significant in the "Middle fault" measured in Ness formation corresponding to relative error of approximately 6 %. Several explanations to such length variety might be proposed as follows. Structurally speaking, "Middle fault" is an incipient fault jointed to the major fault and hence supposed to have a point with zero offset. Consequently, the length of the fault polygons throughout the horizons may significantly vary. Additionally, the considerable difference in length of fault polygons representing entire fault surface might be consequence of non – consistent editing of the ends of fault polygons.

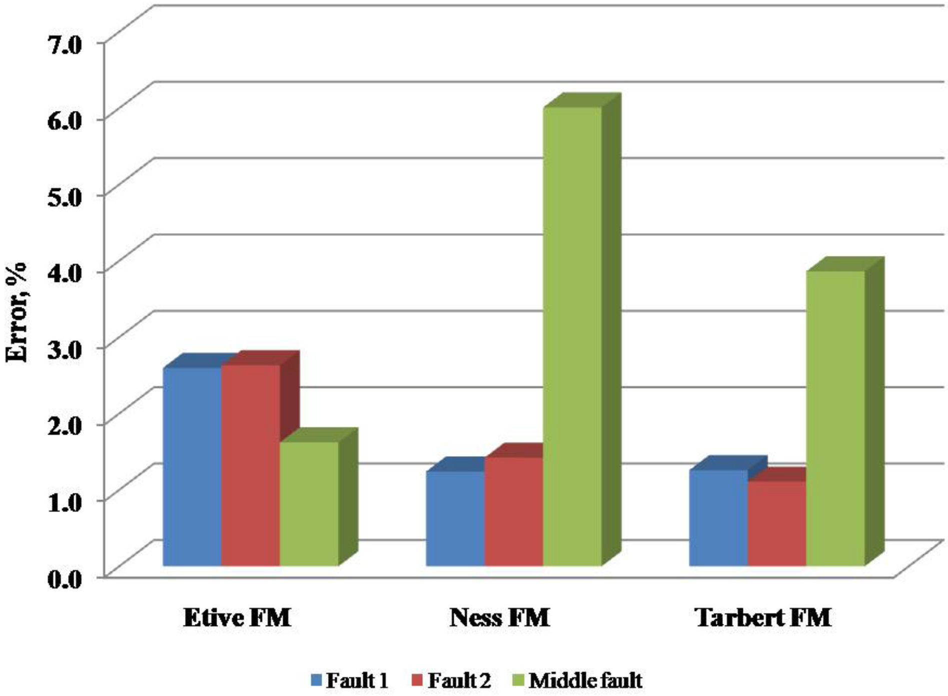


Fig.7.3 Error estimation in the length of the fault calculations

8. Seismic interpretation and structural modeling. Domino faults.

8.1 Data set for interpretation

As it might be seen from previous chapters, the seismic data set includes the entire Gullfaks field with its satellites. Since the project is dedicated to the analyzing of the particular 4A fault block, the subsurface interpretation is carried out for Domino faulting area in order to map major faults that could probably exhibit additional tectonic-sedimentations relationships. So fault blocks *5, 4A, 3* and partly *2* are the objects of the interpretation (an author refers to general nomenclature of the Gullfask field, shown on fig. 3.1).

In terms of key horizons within the Brent Group it was decided to focus on Tarbert, Upper Ness, Lower Ness, and Etive formation as well as the Base Cretaceous Unconformity that is used as a top horizon in structural model. Additionally subsurface data suggests the partial eastwards erosion of strata, Tarbert in particular. Therefore some additional air interpretation of the Tarbert FM had been done.

In order to achieve the consistent results through analyzing reliable data and according to considerable amount of seismic to interpret to it was agreed to be committed to the interpretation philosophy as follows.

1. Primary focus is put on North-South normal faults with picking every 10-th seismic line and trace.
2. Interpret key horizons by mapping every 5-th line and trace.

The background and general trend for interpretation was reached by generating synthetic seismogram for one of the wells in order to tie seismic to well logs. The result is shown in fig. 8.1.1. Despite the significant influence of wash outs on log quality (assumption is made on analyzing of caliper log) the shale-bearing formations, Base Cretaceous in particular, shows the perfect match between synthetics and well seismic. A considerable mismatch is observed in Top Rannoch reflector characterized by rapid increase of both caliper and bulk density readings. In other words significant washouts appeared to be within the Rannoch Formation affected the quality of density and sonic logs which are the crucial data for generating synthetic seismogram.

Previous studies on the subject together with detailed analysis of both 3-D seismic data and well logs suggest the stratigraphic subdivision of the Brent Group as it shown on fig. 8.1.2.

General interpretation of one of the seismic lines with primary focus on Domino System faults is given on fig. 8.1.3. Note that the Tarbert Formation was completely eroded on the western part of the System (fault block *5*) with partial erosion within the *4A*, *3*, and *2* blocks.

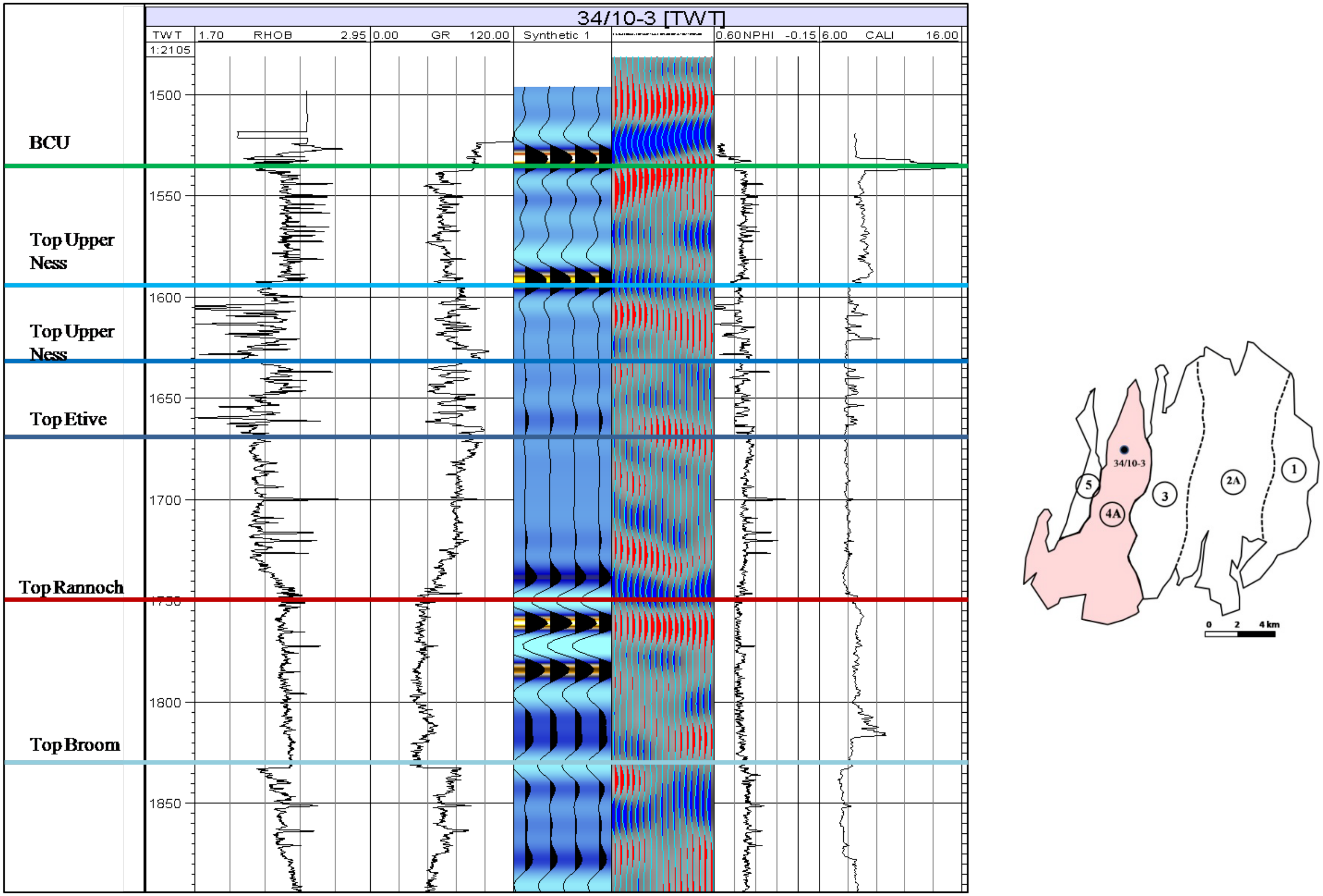


Fig. 8.1.1 Correlation of synthetic seismogram with well logs and well seismics.

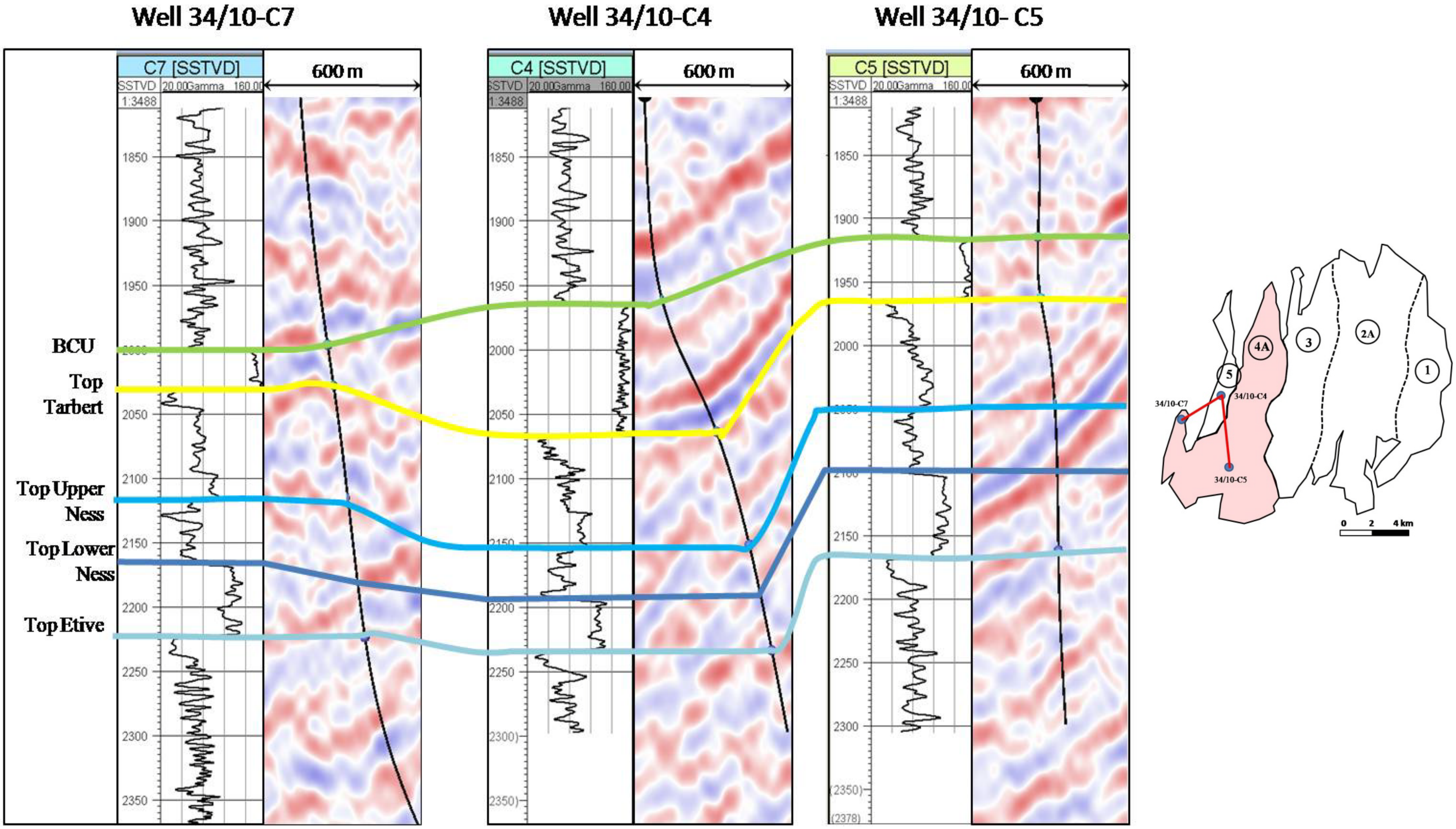


Fig. 8.1.2 Correlation of wells 34/10-C7, 34/10-C4, 34/10-C5.

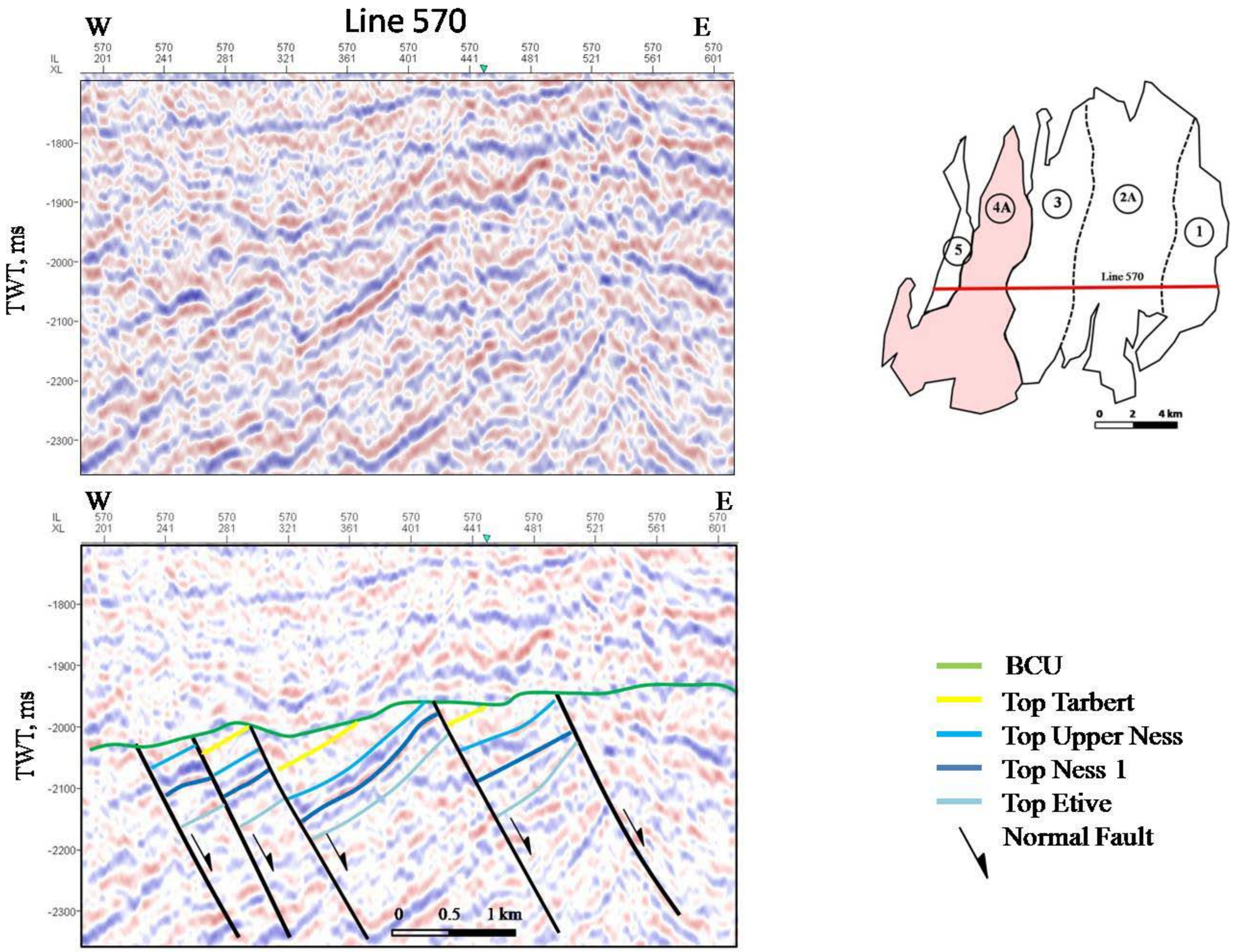


Fig. 8.1.3 Interpretation of the seismic line 570

9. Results and discussion

9.1 Fault-displacement diagrams. Entire Domino System faults area

Primarily it was decided to perform a fault-displacement analysis for major North-South boundary faults with emphasize on *4A* block. Fig. 9.1 represents the structural map of Upper Ness formation with fault polygons and correspondent fault-displacement diagrams for crucial four faults.

Despite the significant fluctuations along the fault length, *Fault 1* shows relatively monotonic increase in throw towards the North with maximum value about 123 m. Those considerable differences in throw appeared as peaks on a curve, might be explained by the relative low quality of the structural model and perhaps links to the interpretation stage that does not fit the general geological concepts.

The most consistent results from fault-displacement analysis are reached by the analyzing of the *Fault 2*. As it seen on a fig. 9.1 this smaller fault had been developed within the data set being able to be observed as a geological feature with beginning and connection to the major *Fault 3*. The minimum value of throw is 12 m, concluding to not consistent mapping of this particular fault during interpretation stage of the project or might be additionally explained by seismic resolution.

The most significant oscillations along the fault length are detected in *Fault 3* concluding to almost impossible observation of any regularity. However the appearance of relative peaks and troughs within the curve could be characterized by relatively same frequency with value about 900 m. Explanation of such behavior of the curve might be as follows. Firstly, such rapid increase/decrease in throw of N-S major faults probably is caused by the existence of W-E minor faults that had not been properly mapped. Secondly, the chosen philosophy of interpretation of each 5-th seismic line brought about to missing some important structural data.

To conclude, the shown in fig. 9.1 fault-displacement diagrams do not allow to provide sensitive analysis of faults behavior with implication to sedimentation-tectonics relations. Hence the more detailed interpretation of the horizons by picking up each seismic line was carried out with some reduction of study area.

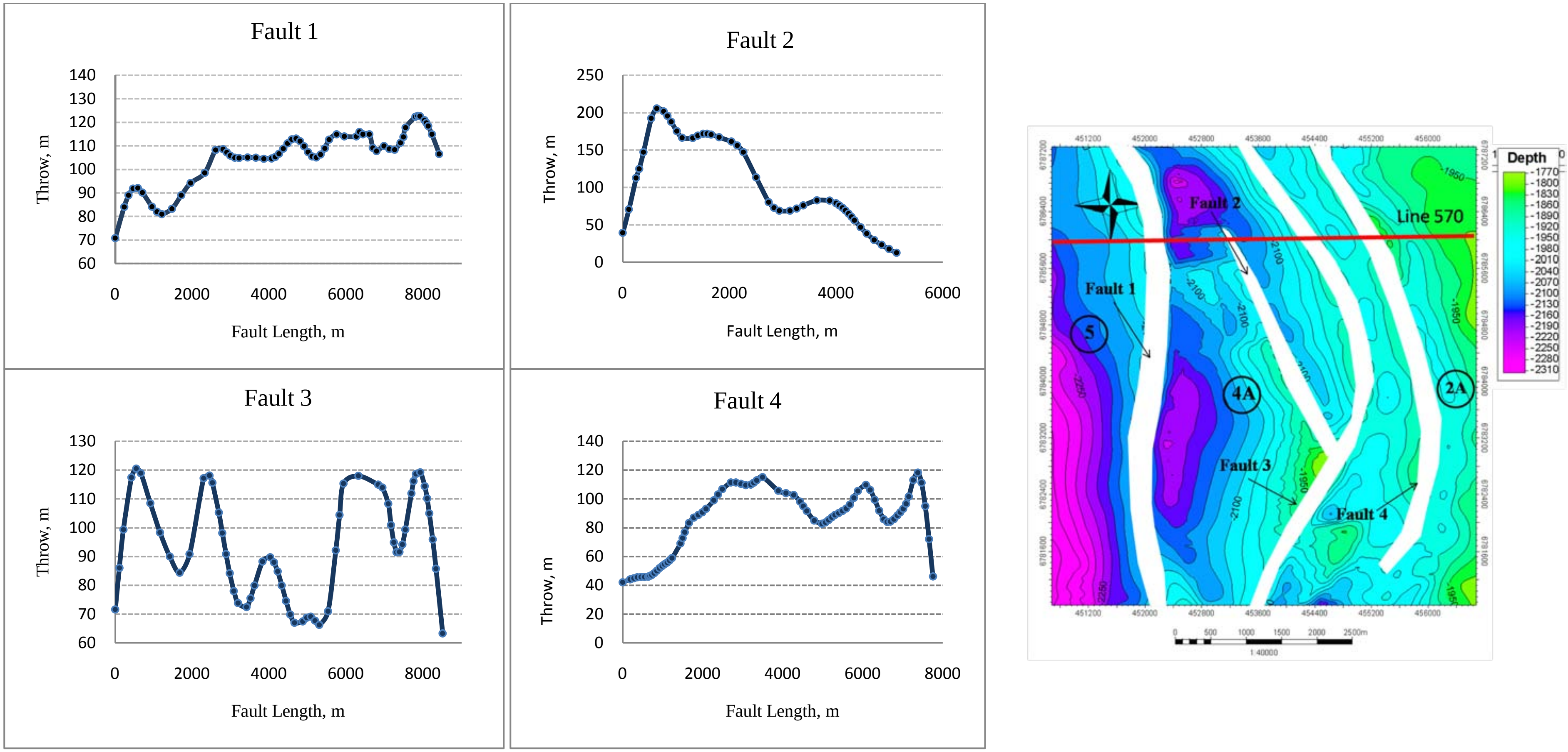


Fig.9.1. Fault displacement diagrams for major faults going through the Lower Ness . Location of the faults is shown on structural map of the Lower Ness formation to the right as well as the nomenclature of the fault blocks.

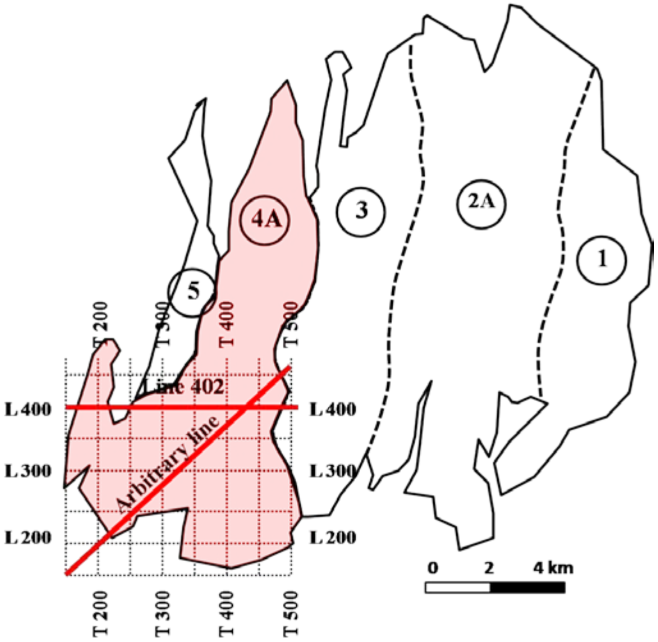
9.2. Fault-displacement analysis for modified data set

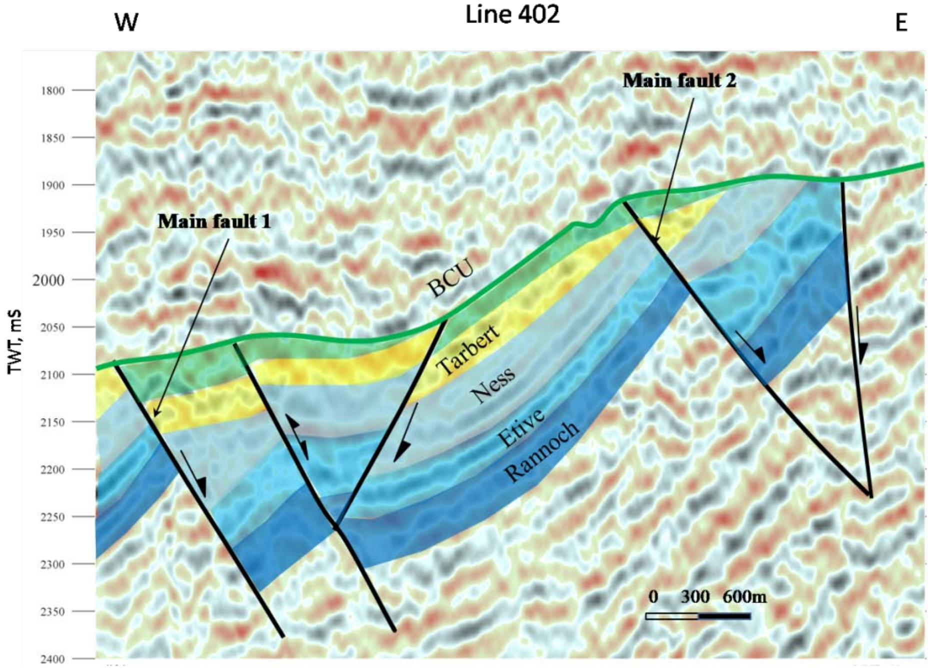
As it was discussed in previous chapter, the more detailed interpretation of given 3-d seismic data set appeared to be crucial in order to get the consistent structural model. Additionally since the tectonic influence on deposition occurred as a syn-rift sedimentation within Upper Ness Formation could be observed only in distinct locations, it was agreed to modify given data by switching to the South-West part of the Gullfaks field with cutting seismic cube as it shown on fig. 9.2.1.

At this phase of the project the procedure for interpretation and structural modeling was chosen as follows.

1. Emphasize on 3 major boundary N-S faults by picking up every 5-th line when mapping faults.
2. Interpret 4 crucial horizons within the Brent Group (Etive, Lower Ness, Upper Ness, Tarbert) and the regional reflector, the Base Cretaceous Unconformity, by picking up every seismic line.
3. Use grid increment of 50x50 m in structural model.

The results of detailed interpretation with structural model of *4A* fault block are shown in fig. 9.2.2. Note that structural model is performed only for upper part of the Brent Group i.e. Tarbert, Upper Ness and Lower Ness formation. In order to show the erosion of the Group Base Cretaceous Unconformity was used as a top horizon in the model. However none of the unconformities had been used in fault analysis structural model since it appeared to be of the great importance to make an air interpretation of the Tarbert Formation with aim to estimate consistent values of the fault displacements. Fig. 9.2.2 shows significant variety in thickness distribution within the Upper Ness Formation with tendency to complete erosion of sediments towards the north (Cross-section A-A). The detailed examination of the fault block consequents to the existence of paleo-island, those distinct locations within the fault block that might be characterized by non-deposition of the Upper Ness leading to Tarbert Formation being superimposed on Lower Ness. From a stratigraphic point of view considerable variation in thickness distribution within the Upper Ness with complete erosion towards the fault crest appeared to be an evidence for tectonic influence on deposition, i.e. syn-rift sedimentation.





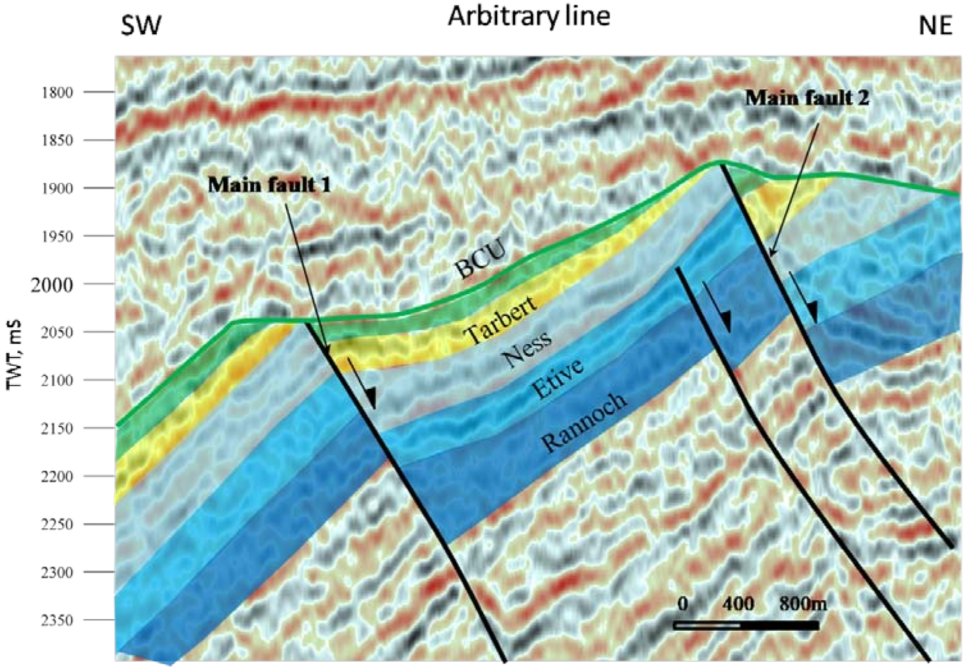
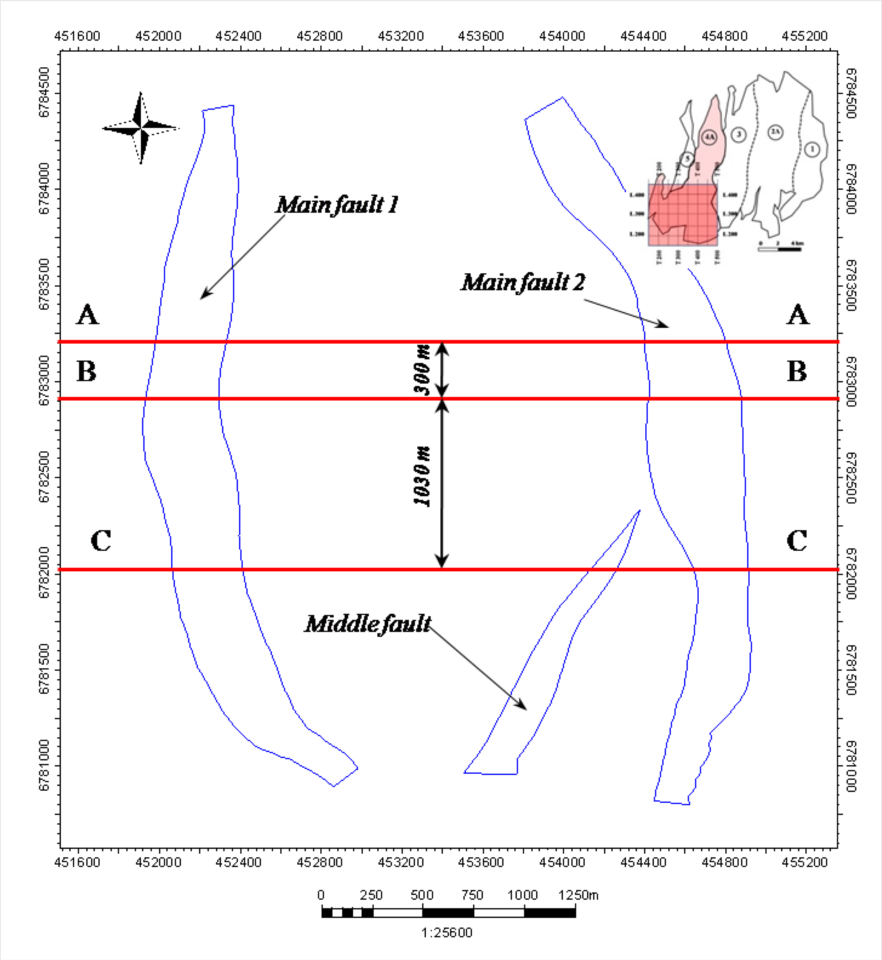


Fig.9.2.1. Modified data set with two interpreted seismic lines showing the Brent Group within primarily 4A fault block. Note nomenclature for faults further used in the project. Seismic data set is cut with final geometry 500 lines x 500 traces and bounded by 1700 – 2400 milliseconds time span and with location in South-West of the Gullfaks field.



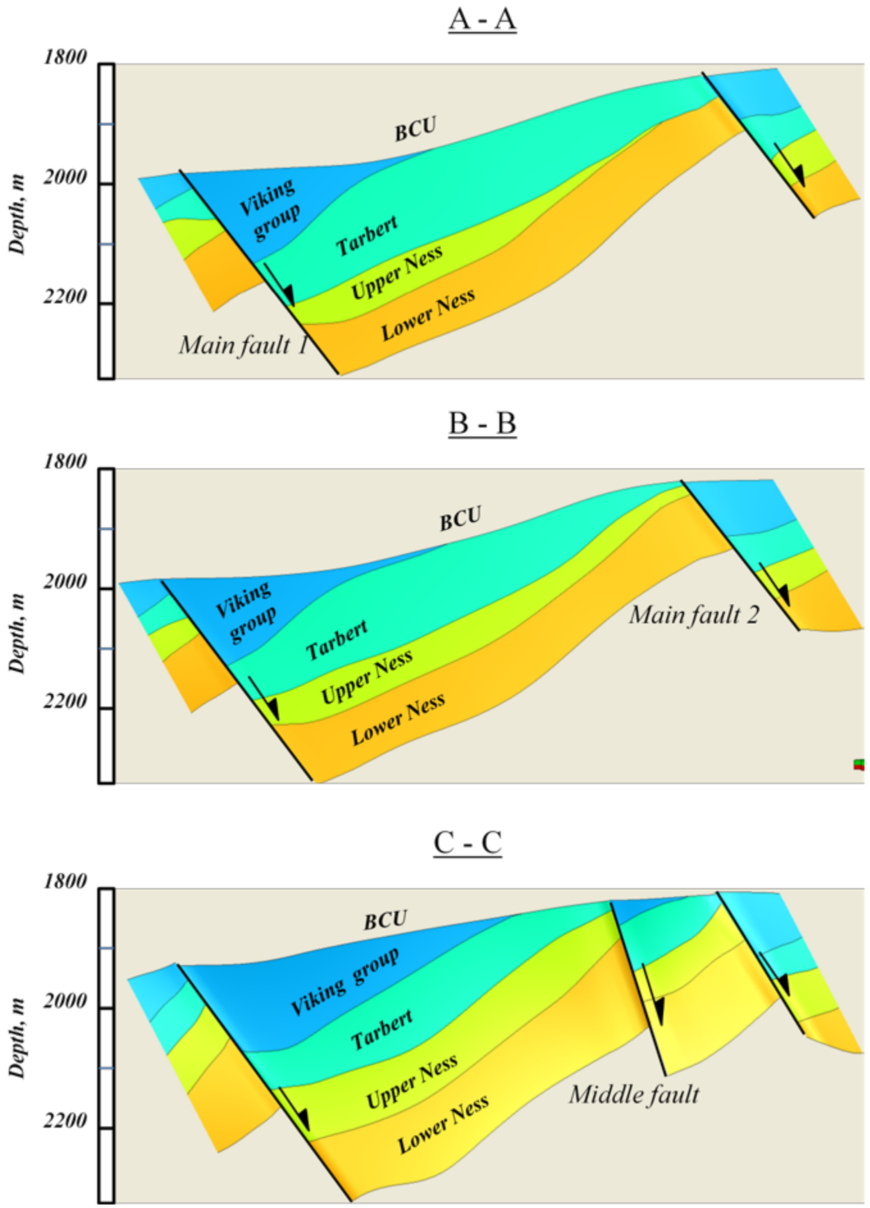


Fig.9.2.2.Map view of the fault polygons within the Lower Ness Formation with 3 different cross-sections (A-A, B-B, C-C). Note the thickness distribution within the Upper Ness formation with significant difference along the North-South trend. Cross-section A-A represents the non deposition of Upper Ness formation and erosion of the Lower Ness on the crest of the fault block

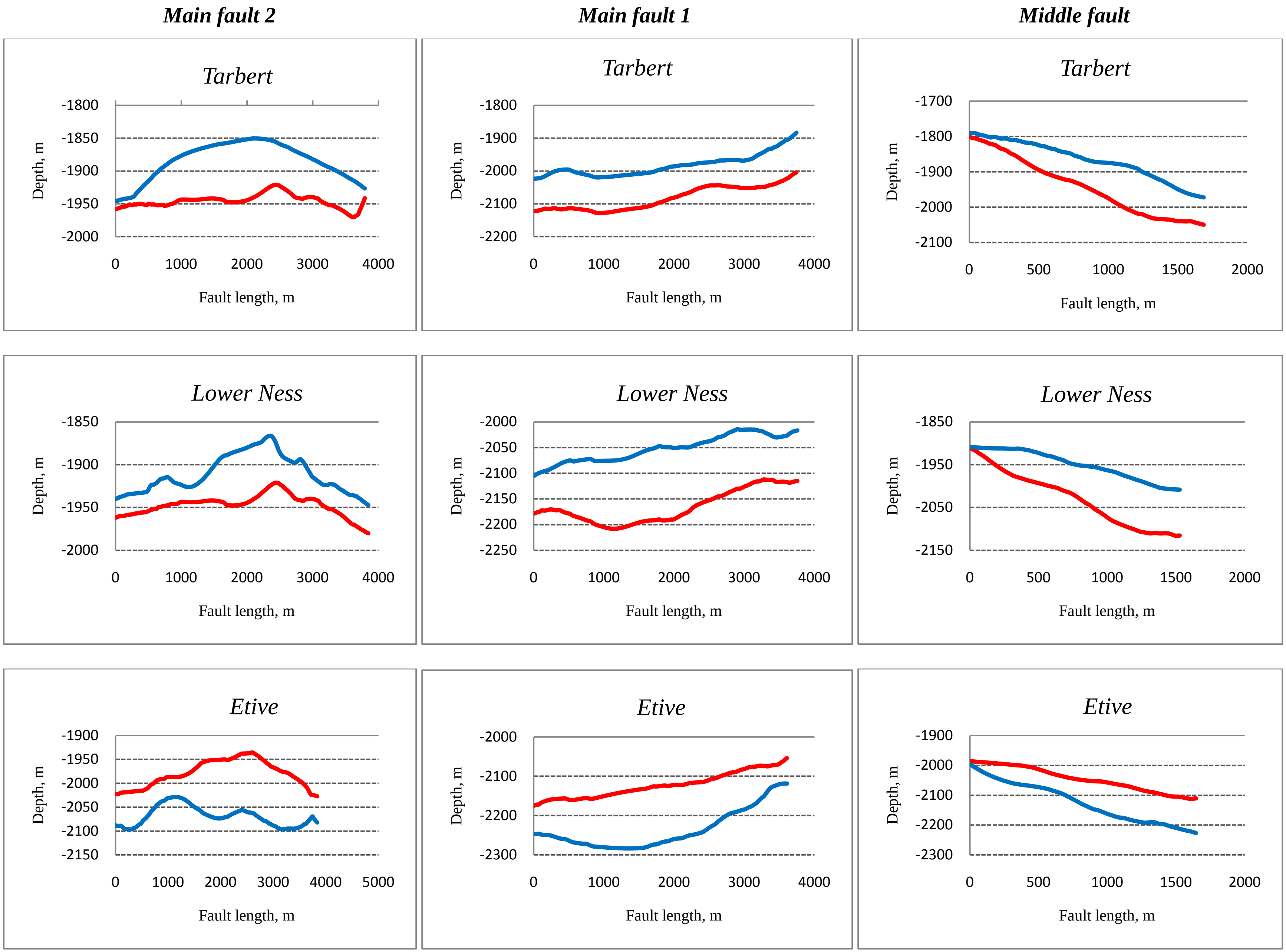


Fig.9.2.3.Fault separation diagrams for major 3 faults. Red and blue curves represent up throw and down throw respectively

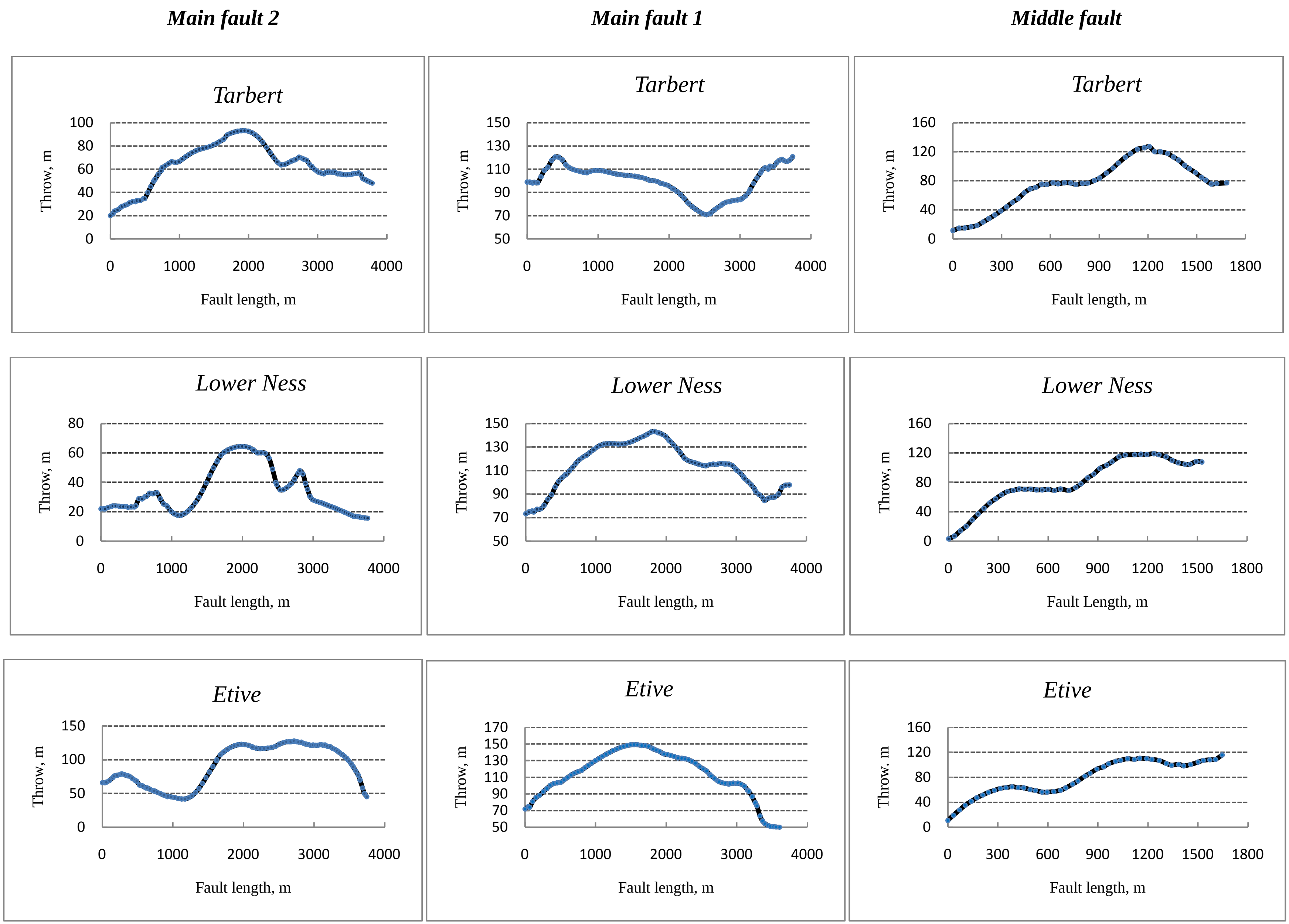


Fig.9.2.4. Fault-displacement diagrams for throw-length of the fault relations. Note significant fluctuations of throw of the Main Fault 2 in Lower Ness Formation with correspondent peaks in the Tarbert Formation.

Another observation made on detailed examination of the structural model of the 4A block is the considerable variation in dip of Lower Ness showing significant increase towards the fault crest (fig.9.2.2, Cross-section A-A) From structural point of view, that scenario might happened as a consequence of different rates of subsidence along the length of the fault or local uplift within the fault block. Whichever event had been taking place during deposition of the Upper Ness, it resulted in existence of paleo-island, a part of the fault block 4A exposed above sea level and characterized by relatively high values of vertical displacement.

A suite of the fault-displacement diagrams performed for the key horizons of the Upper Brent Group is shown in fig. 9.2.3 and 9.2.4. Generally speaking, all the faults investigated in study (*Main Fault 1, Main Fault 2, and the Middle Fault)* include the large displacement fault zones.

Since the Upper Ness was completely eroded (non-deposited) in particular locations of the fault block it was agreed to avoid its fault-displacement analysis and focus primarily on the Lower Ness interval. Significant fluctuations along the fault length, as it shown on fig. 9.2.3 to the left, were observed only in *Main fault 2* linking to the fault control on deposition and probable local uplift in the Middle Jurassic. The shape of both upthrow and downtrow curves within the Lower Ness Formation appeared to be almost identically oscillating with links probably not only to local uplift or different rates of subsidence but also to existence of minor cross West-East faults. Note also the same shape of the downtrow of *Main Fault 2* in Tarbert formation. Those peaks on a curve almost reflect the downtrow curve in Upper Ness that probably may link to the existence of reverse cross West-East fault that might have been evaluated after the deposition of the Brent Group during inversion of the basin in Mesozoic. In other words at least 2 local uplifts affected the final sedimentary patterns of the fault block *4A*. The earliest one that might happen during deposition of the Brent Group in the Middle Jurassic was responsible for existence of paleo-island in particular. The different rates of rotation and subsidence combined with transgression that probably occurred just after the uplift determined the syn-rift character of deposition of Upper Ness sediments. The second, the Mesozoic inversion of the basin, caused the final architecture of the fault block *4A* with cross West-East reverse faulting propagation combined with reactivation of the major boundary faults.

Both *Main Fault 1* and *Middle Fault* according to fig. 9.2.3 represent the continuous growing and propagation within all examined intervals. Both downtrow and upthrow curves reflect each other with expected throw to be almost constant along the lengths of the faults. Since the *Middle Fault* was initiated within the given data, the displayed values for upthrow and downthrow are equal with minimum value at the point of connection with *Main Fault 2* for all of the intervals.

The throw-length of the fault cross-plot shown for all of the examined faults in fig. 9.2.4, displays how does the fault geometry vary over different length scale. For instance, the shape of the throw-length curve for *Main Fault 1* occurred as a smooth line with maximum values of throw 140-150 m being properly taken on a half of the fault length. Such character of throw distribution supports the assumption made by Barnett et al. (1987) who proposed that displacement is zero at the fault tips and usually increases to a maximum near the center of the fault surface. From an author point view that statement might be applied as a consistent prediction tool in order to estimate the proper length of the fault which is obviously exceeds the modified data set.

Fault displacement diagrams performed for *Main Fault 2* represent the oscillating character of the throw curve with rapid increase from 40 to 60 m in Lower Ness Formation. Since the displacement within the rock volume varies from one layer to another with considerable difference, the magnitude of the faulting within particular formations additionally depends on not only regional extension but also on ductile deformation and rotation/subsidence ratios. In other words, the rapid increase in throw within Lower Ness formation might be explained as a consequence of combination of different structural and rock mechanics events. From structural point of view, the examined in the study *4A* rotated fault block experienced a different rotation/subsidence ratio along the *Main fault 1* and *Main Fault 2* with major circumstance in existence of paleo-island (fig. 9.2.5). In more detailed the considerable rotation with comparison to subsidence of the fault block caused the local uplift of the fault crest seen on fig. 9.2.4 as a rapid increase in throw of *Main Fault 2*.

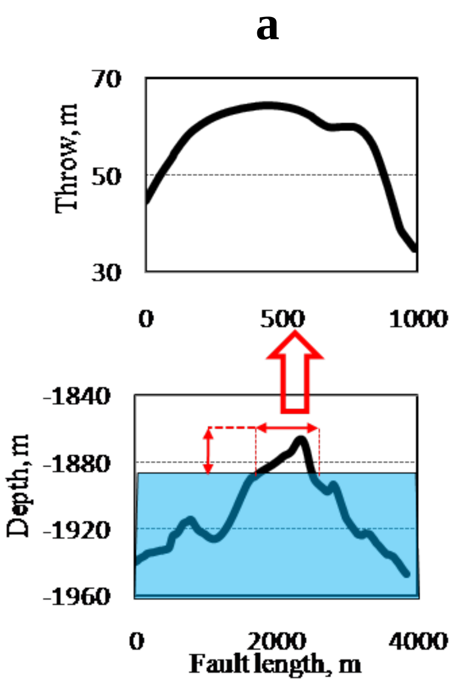
Used in the study fault displacement approach might be useful in interpreting seismic reflection data both for quality control of interpretations and for quantities extrapolation of limited data. Obviously the more fluctuations does experience the curve of the throw-length cross plot, the bigger error in interpretation of subsurface data. Discontinuities and marked irregularities in the throw pattern and abnormally high or low values indicate interpretive error. However syn-sidementary faults such *Main Fault 2* intersecting a free surface during formation has systematic variations of throw (fig. 9.2.4, Lower Ness Formation in particular) but could be characterized by less symmetry in displacement curve.

The decrease in displacement in the direction of the fault – normal in all examined faults had not been observed in the study. Only *Main Fault 1* shows decreases in throw value from the maximum 150 m in the Etive Formation to the minimum 70-90 m in the Tarbert Formation. At the same time the *Middle Fault* characterized by the same character of the throw pattern in all investigated formations represents the relatively similar maximum throw values around 120 m consequently showing the same magnitude of fault growth magnitude within Etive, Lower Ness, and Tarbert Formations.

9.3 Evidence for paleo-island existence

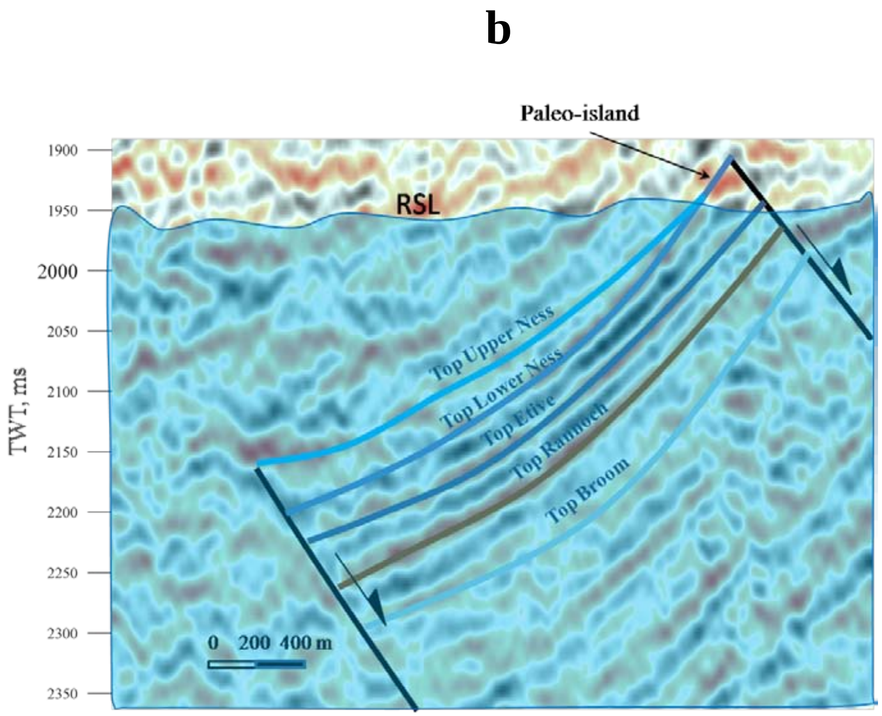
As it was proposed in previous chapters (an author refers to chapter 6.2 and fig. 6.2.2 in particular), the detailed interpretation of the seismic lines suggests the existence of paleo-island in the Upper Ness time that might be observed as a topographic high at the surface. Fig. 9.2.5 shows the paleo-island with evidence found from throw-length of the fault cross plot (section a) and interpretation of seismic line. Basically subsurface data suggest the onlap deposition of the Upper Ness on the Lower Ness as a circumstance of change to transgressive cycle. Upper Ness being interpreted as lacustrine deposits associated with some coal and shale beds is related particularly to the marine environment. In other words the paleo sea level was put on a depth where the Upper Ness is represented by the zero thickness or at the point where the Tarbert Formation was superimposed on the Lower Ness. According to seismic data such sea level was estimated at the depth of 1882 m by applying available check shot data. The dimensions of the island are as follows.

1. The length of the paleo-island is approximately 950 m.
2. The maximum height above paleo-sea level is 20 m.



L = 950-1000 m.

H = 20-25 m.



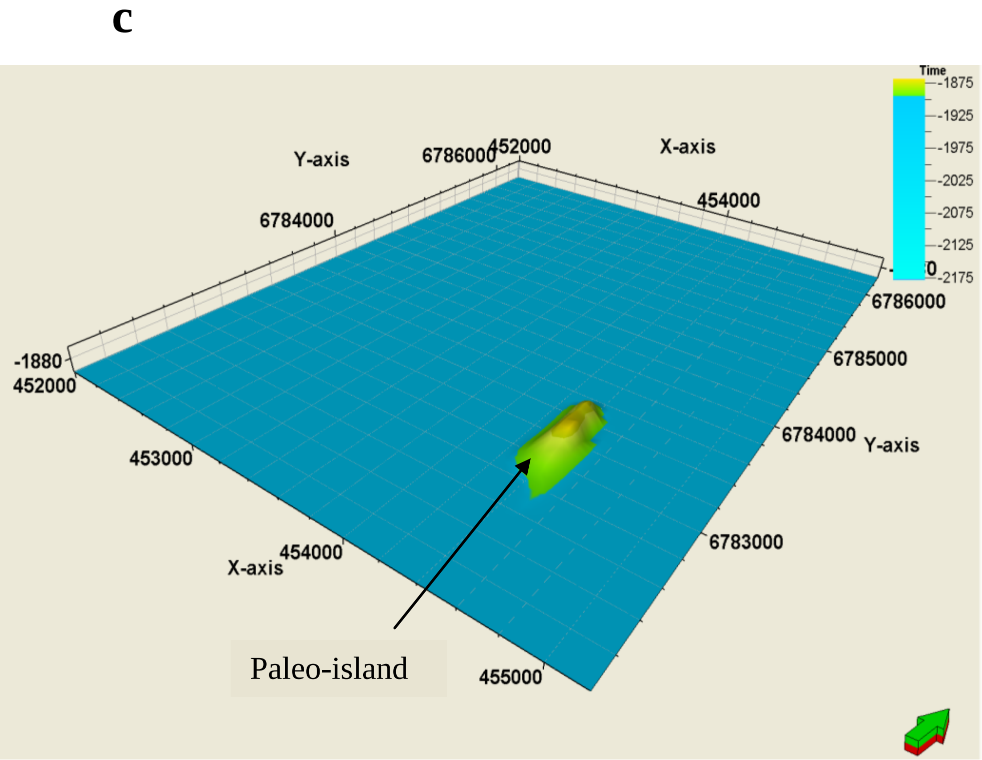


Fig.9.2.5. Evidence for existence of paleo-island in the Upper Ness time. ***a*** *shows upthrow of the Main Fault 2 together with correspondent throw-length crossplot within the Lower Ness Formation with estimated length L of the island and height H above the paleo-sea level.* ***b*** *represents the interpreted seismic line with proposed paleo-sea level at the point of non deposition of the Upper Ness Formation.* ***c*** *gives the general location of the paleo-island regarding UTM coordinates.*

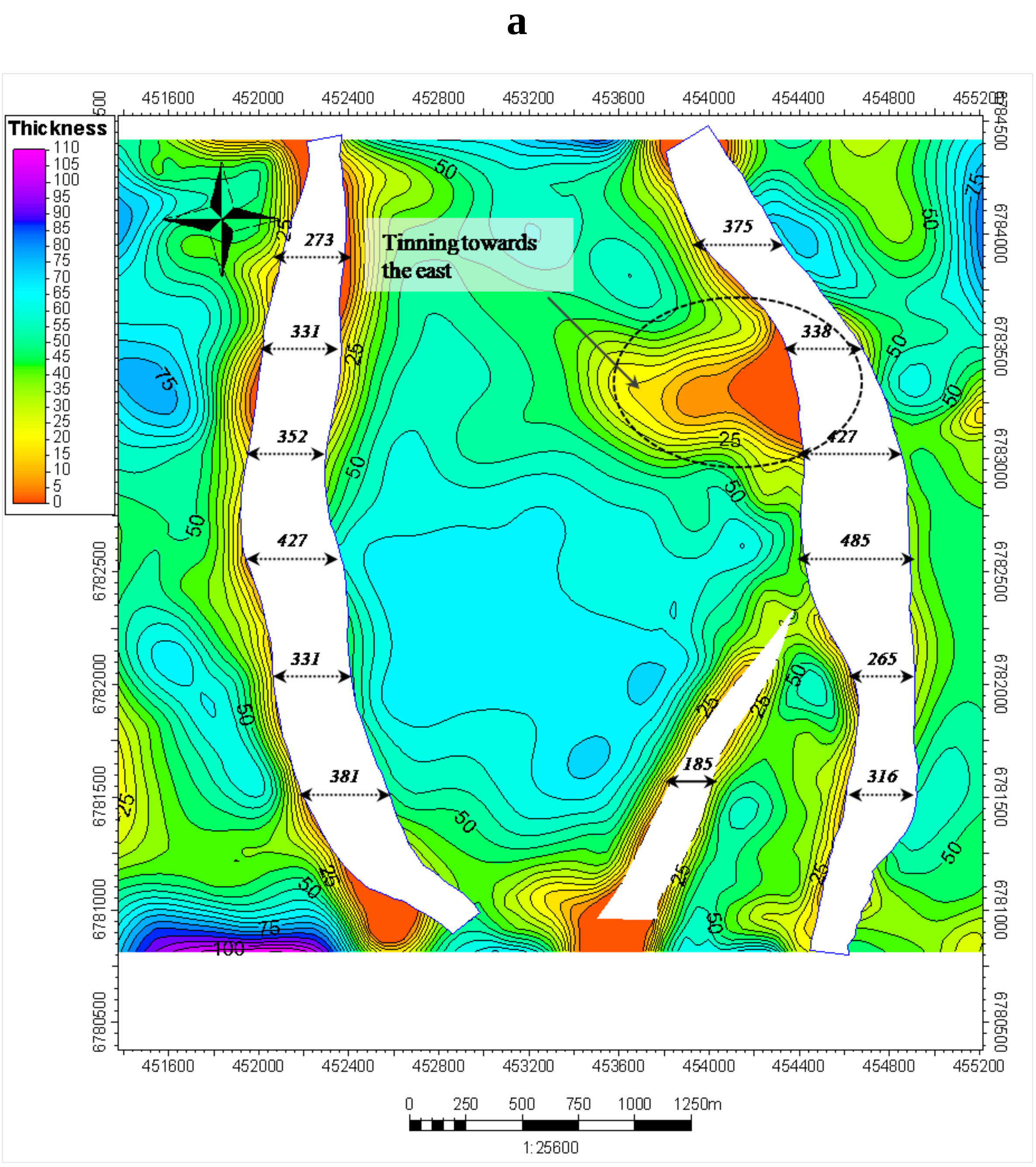
To summarize, the evidence for existence of paleo-island is extracted from analysis of the fault-displacement diagram for the *Main Fault 2* within the *Lower Ness Formation* which shows the rapid increase in throw value seen as a peak on a curve. The change of the slope in a curve may additionally represent the erosion of the Lower Ness that might be supported by the dip analysis performed for the all formations in the next chapter of the project.

9.4 Thicknesses analysis and dip maps approach

Detailed isopach maps performed for the Upper Brent horizons are shown in fig. 9.4.1 and – 9.4.2. Analysis of the thickness distribution within the Upper Ness Formation brought about the tectonic control on deposition appeared as significant difference in thickness patterns. The obvious thinning eastward with zero sediments at the crest of the faulted block directly corresponds to the hypothesis of syn-rift deposition of the Upper Ness. The maximum thickness of about 70-75 m is observed towards the hanging wall of the block. Non deposition of the Upper Ness with zero thickness might be found on the fault crest. However such thickness distribution within the fault block does not directly corresponds to the maximum displacement (heaves) value that could be found towards the south and reached the value of about 500 m.

Lower Ness as it shown in fig. 9.4.2 is characterized by relatively homogeneous distribution of the sediments along the axis perpendicular to the fault surfaces. Such almost flat topography of the horizon might be interpreted as pre-rift sedimentation. The maximum displacements for the Lower Ness formations lie within 490-500 m limits being on the same magnitude as the superimposed Upper Ness Formation. The rapid increase in the thickness in that location characterized by the maximum displacement does represent the paleo-island in Upper Ness time which is directly corresponds to the Upper Ness isopach with zero thickness.

Thickness patterns within the Tarbert formation show the existence of considerable depocenter (fig. 9.4.2 b section) with maximum column of sediments up to 110 m. Such availability of accommodation space might be explained by the thinning and irregular distribution of sediments within the underlying Upper Ness Formation with fault control on deposition.



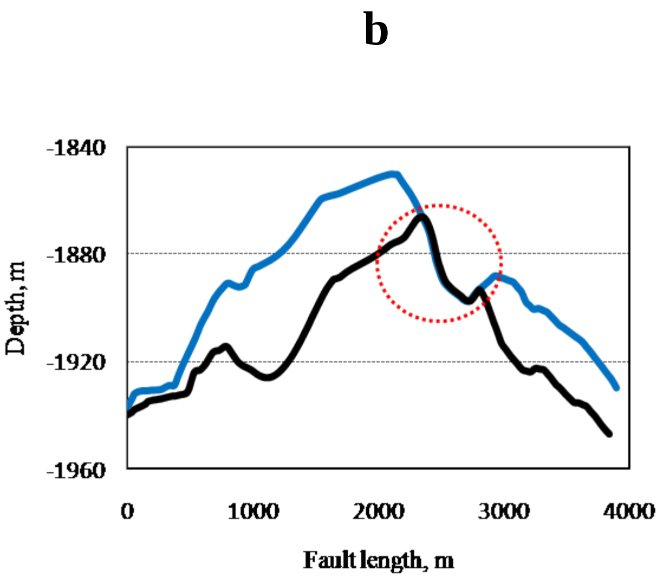


*Fig.9.4.1 Isopach map of the Upper Ness Formation (**a**) with correspondent fault-separation diagram (**b**) of the Upper Ness (in blue) and the Lower Ness (in black). Note syn-rift deposition of formation appeared on a map view as thinning towards the fault crest (towards the east). The area in white limited by polygons introduces displacement (heaves) of the faults with measured values.*

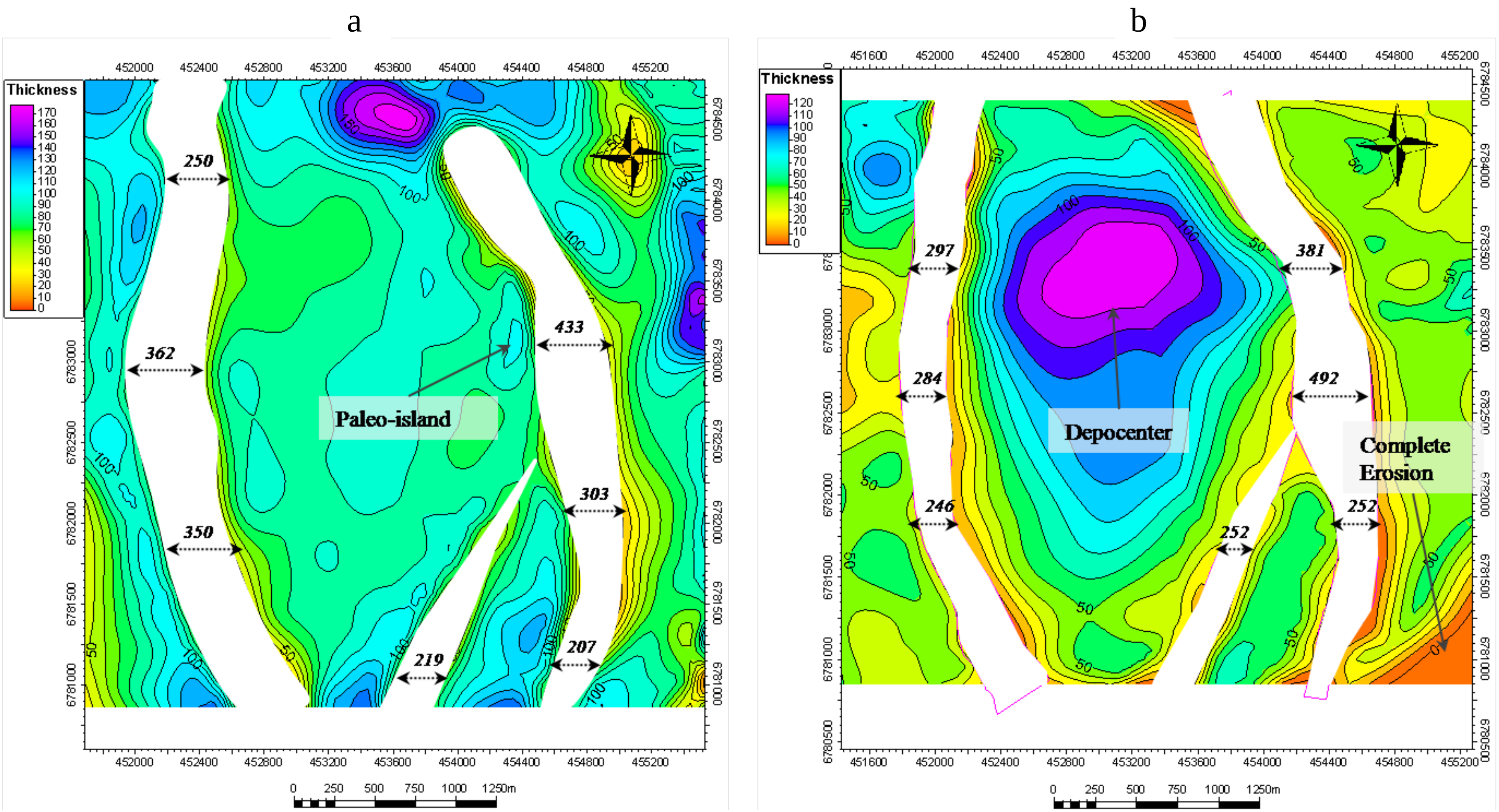


Fig.9.4.2 Isopach maps of ***a*** *Lower Ness and* ***b*** *Tarbert formations. Note the almost flat topography of Lower Ness formation showing insignificant variation of thickness distribution within faulted block. Contrary, Tarbert formation represents considerable variation of thickness patterns caused by availability of additional accommodation space due to thinning of underlying Upper Ness. Values represent the heaves of faults.*

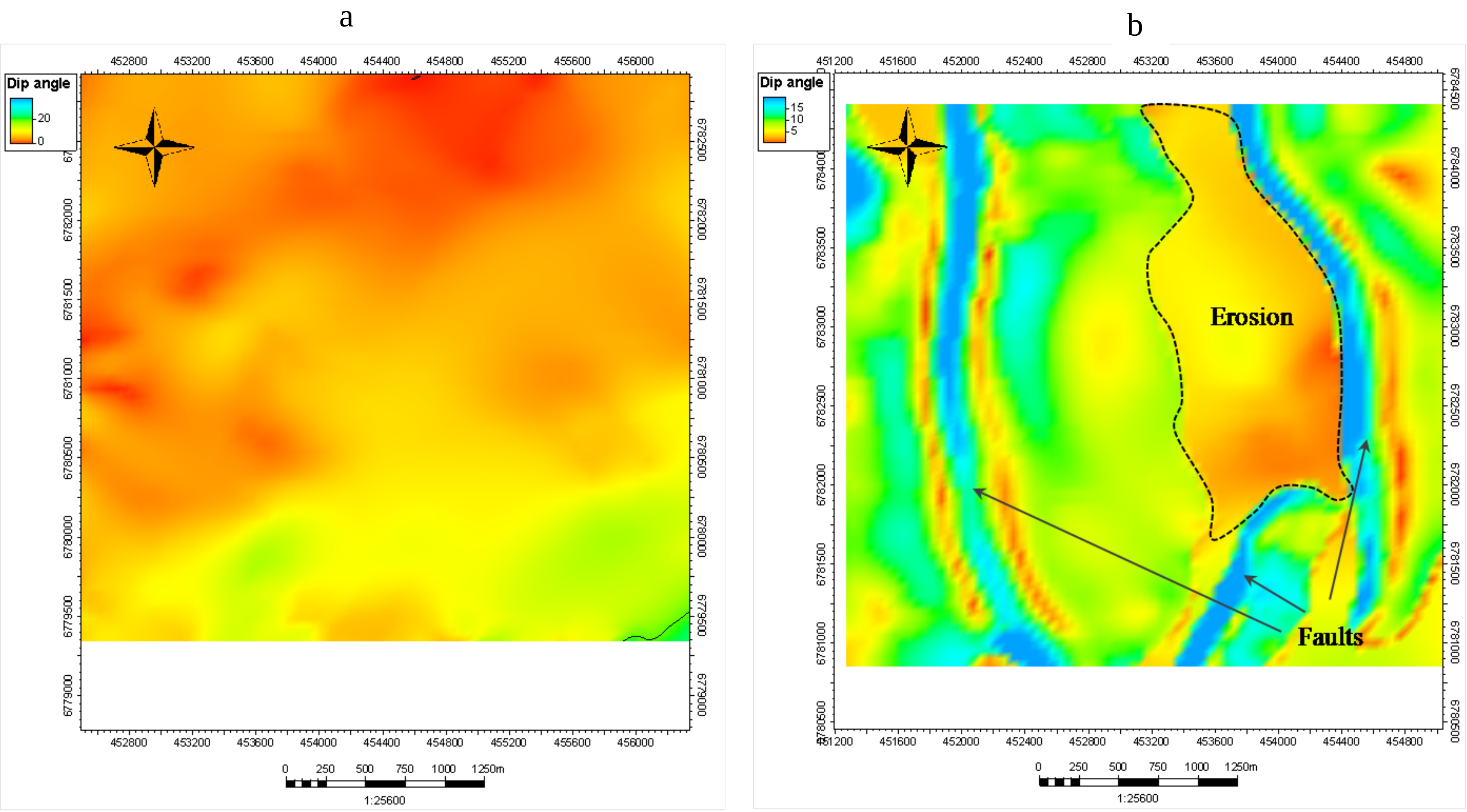


Fig.9.4.3 Dip maps. ***a*** *shows distribution of dip within Bace Cretaceous Unconformity dipping 4-6 degrees south east.* ***b*** *represents dip map for Tarbert formation. Area appeared as a result of rapid change in dip angle and dashed in black represents the amount of Tarbert formation been eroded.*

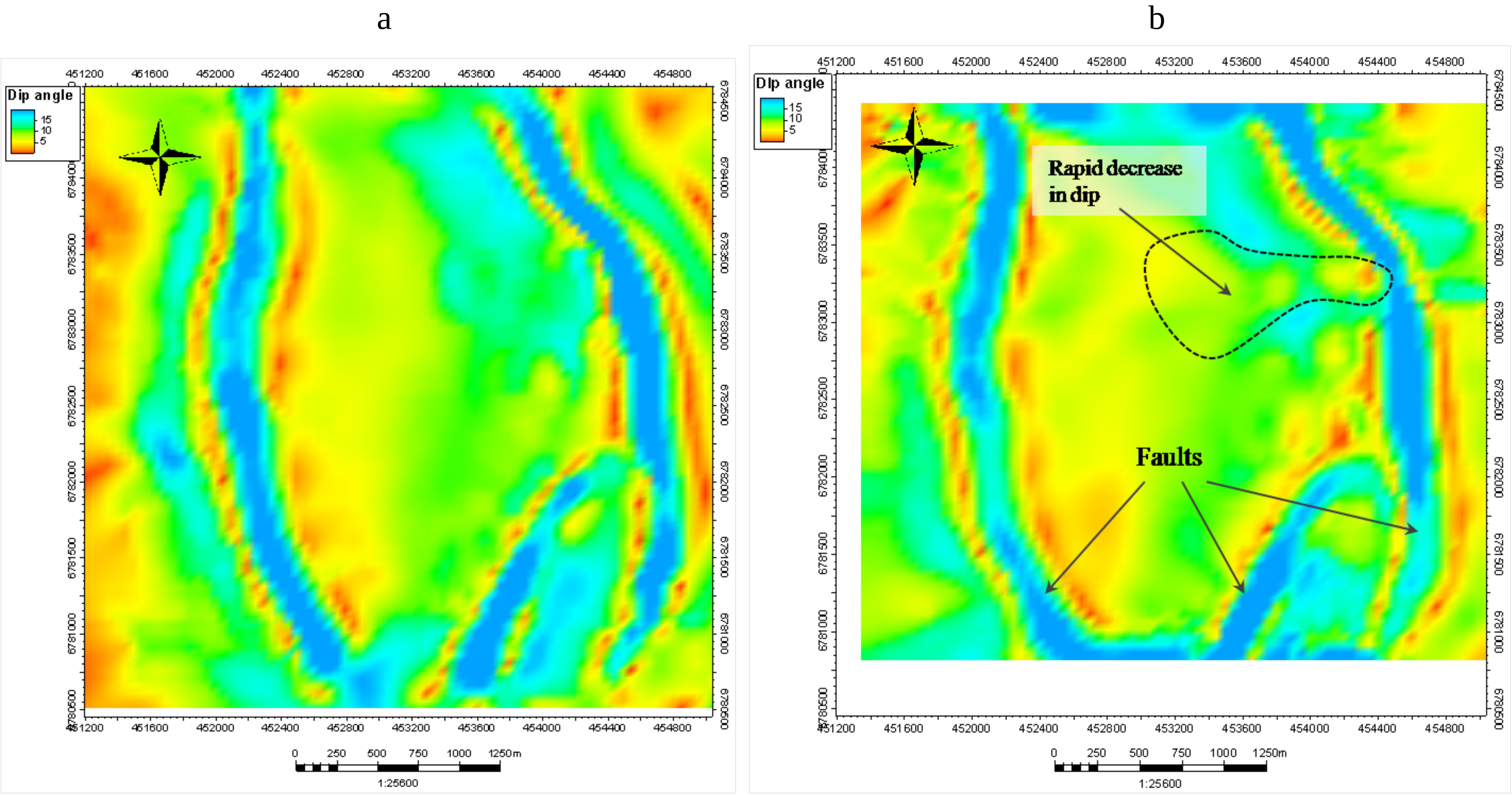


Fig.9.4.4 . Dip maps. ***a*** *Dip map of Lower Ness Formation. General observation is eastward increase in dip up to 10-11 degrees.* ***b*** *shows dip map of Upper Ness Formation. Note eastward decrease in dip below 2-3 degrees level suggesting syn-rift deposition of Upper Ness.*

Dip maps generated for the Upper Brent Group formations are shown in fig. 9.4.3-9.4.4. Base Cretacuous Unconformity respresenting the surface that hab been significatly affected by the erosion shows almost constant dip values within the range of 0-7 degrees towards the south east. However the surface is stippening on the south west of study area in some places exceeding values of 12-13 degree. Such change in the slope probably might be explained by the existence of the considerbale fault with significant displacement controlling the accommodation space that is obviously was underfilled.

Tarbert Formation (fig. 9.4.3) appeared to be significantly affected by the post depostion events such erosion. The dip map shows the rapid decrease towards the east with maximum difference 10 degrees. Thefeore the tabular area inside the dashed ine on fig. 9.4.3, b section directly corresponds to the erosion of the Tarbert Formation with final dip angles influenced primarily by post-rift events.

The upper Ness Formation appeared to be stippening towards the east with final dip value about 13 degrees on the fault crest. Such final topography of the horizon might be explained by the reltions betweet rotation, subsidence and sedmient supply during deposition. In other words the stippeining of the formation is might be the direct circumstance of the tectonic influence (the constant rate of the fault rotation) on deposition of the Upper Ness Formation.

Rapid decrease in the dip on a disticnt location with comparing to the rest of formation within the Lower Ness might be interpreted as the erosion or non deposition of the Upper Ness as it shown on fig. 9.4.4 b section.

9.5 Tectonic influence on sedimentation. General Implication

Fault control on deposition of the Upper Brent Group might be seen on evolution of the fault-displacement diagrams throughout geological time as it shown in fig. 9.5.1.

Basically sedimentation in extensional basins is controlled by a complex interaction between:

- Sediment supply
- Faulting block rotation creating tectonic slopes and topography

- Subsidence and climatic change responsible for relative sea level with characteristic features.

The structural and stratigraphic record of many extensional basins reflects predominantly vertical tectonic movements. The Viking Graben and related Shetland basin could be characterized by a long subsidence history related to major orogenies with different rates, uplift and non-deposition was followed by rapid subsidence. Brent Group which was deposited from Aalenian to Late Bajocian could be divided into 2 major sections with a boundary as Upper Ness formation representing change in depositional environment since the change in transgression / regression cycles. According to a number of publications, the East Shetland Basin of both the UK and the Norwegian Sectors of Northern North Sea containing about 15 billion barrels of recoverable oil (Bowen, 1991) had been formed through several rifting stages characterized by different rates of subsidence and extension. However, the major phase of rifting is believed to be appeared in Late Jurassic and was responsible for final basin architecture and facies distribution. Consequently the main geological features within the basin are huge tilted fault blocks bounded by eastward dipping domino faults with common values of 30 degrees. It is generally agreed that the subsidence provides the first order control on deposition of sediments. In other words the accommodation space for sediments to be filled is a function of subsidence magnitude and rates. Together with sediment supply subsidence determines whatever the basin is over- , under- or properly filled. The 3-d seismic data with review of recent publication suggest that the East Shetland Basin had been filled by Brent Delta sediments progradating westwards with no significant sign of syn-rift erosion. Consequently such an interpretation suggests the relatively same magnitude of both sediment supply and subsidence.

Another integrated approach taking into account interplay between tectonics and sedimentation applied for exploration needs might be the careful investigation of extreme strata forming mechanisms such rapid subsidence giving a link to petroleum potential. The more detailed approach from extensional settings of Barents Sea proposing high petroleum prospectively as a function of combination between rapid both subsidence and sedimentation rates is given by Galieva (2009).

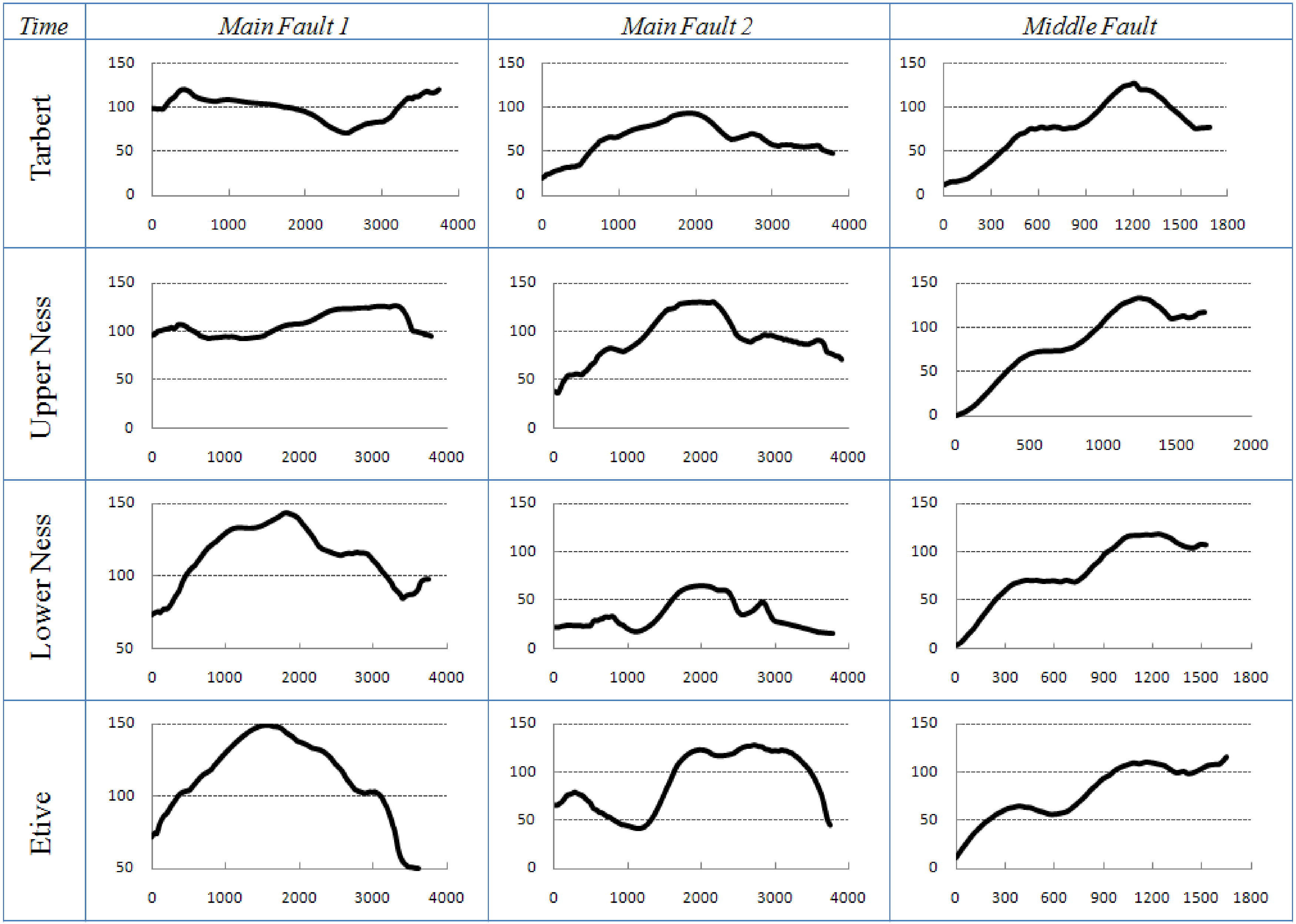


Fig.9.5.1 Fault displacement diagrams put in geological time order. Note considerable variation of fault growth within the Main Fault 1 and Main Fault 2 in the Upper-Lower Ness intervals. X and Y axes represent the length of the fault and throw in m.

Controls on sedimentation within the Ness formations and Upper Ness in particular are demonstrated by the distribution of the depositional environments and their relationships to local and regional structures. Thickness distribution of the Upper Ness comparing to the Ness formation shows significant difference in sedimentation patterns. As it might be observed from seismic data set, thickness distribution of the Upper Ness represent thinning eastward with almost zero sediments towards the crest of the fault. However that kind of distribution of the sediments might be observed on particular places of the Gullfaks study area which is approximately limited by seismic lines 365 and 410. From length of point of view this segment of the rotated fault block could be represented by a value of 1 km. Seismic data set combined with isopache maps of both Ness and Upper Ness suggests the local uplift of the rotated fault block resulted in change of relative sea level and hence onlap deposition of Upper Ness onto Ness formation with thinning and partial erosion of sediments on the exposed crest of rotated fault block. Contrary the different rates of subsidence along the fault might cause the existence of proto-island, a locality within Gullfaks field probably described by relatively small subsidence comparing to the rest of the fault. Another evidence of subsidence control deposition of Upper Ness could be extracted from sensitive analysis of dip maps generated for all of the key reservoirs of Brent Group. From author points of view the consideration of the lowest successions in the Brent Group, Broom and Rannoch could not bring any contribution to the evolution of tectonic control sedimentation hypothesis and hence, only Etive, Ness, and Tarbert formation were taking into account as those with distribution of the depositional patterns strongly controlled by the tectonic activity.

Additionally interplay between tectonics and sedimentation does contribute to the estimation of timing of particular faults. As it was described in previous chapters the major rifting phase responsible for formation of Middle Jurassic rotated fault blocks have been appeared in Late Jurassic proposing pre-rift deposition of entire Brent Group sequence. However by sensitive analysis of available 3-d seismic data and some seismic attributes an author would like to argue the particular timing of major rifting stage. Figure 9.5.2 shows the cross-section through the same rotated fault block 4A. As it might be observed from seismic line 479, some of the formations below Lower Ness are characterized by different thickness distribution along the width of the fault block. This particular scenario is typical for syn-rift deposition and sedimentation controlled by not only

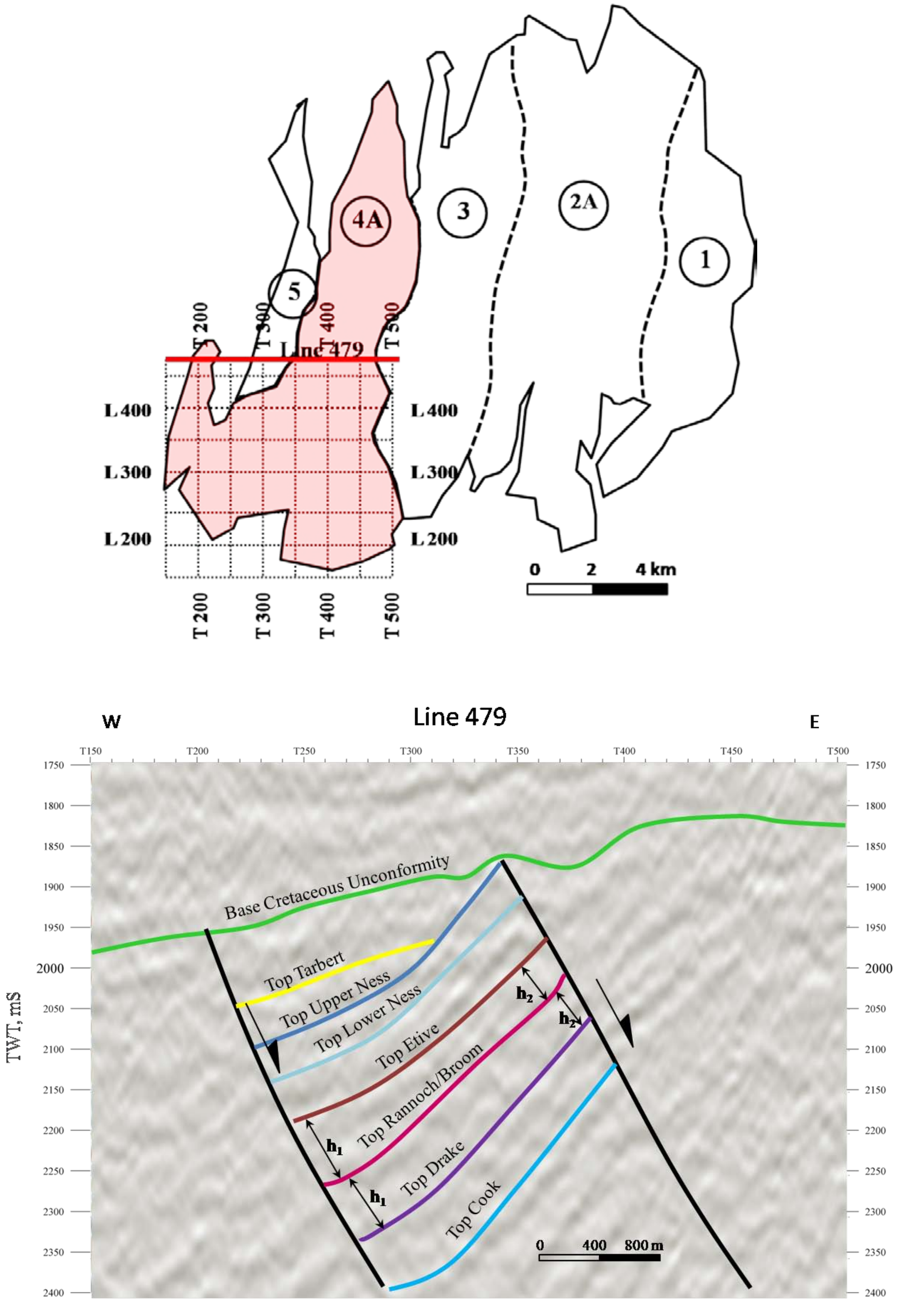


Fig.9.5.2 Location and the interpretation of seismic line 479. h_1 and h_2 represent the thickness measurements which significantly vary due to syn-rift deposition.

subsidence but also rotation. In other words, different thickness distribution within Etive, Rannoch/Broom and Drake formations suggests the relatively earlier age of the fault growth with initiation prior to deposition of Brent Group in Pliensbachian-Toarchian, Lower Jurassic age. The absence of significant variations of thicknesses in Upper Ness and almost parallel strata may propose change of subsidence/rotation ratio with turn to thermal subsidence only. However, there is still a question opened for detailed analysis and discussion – why the typical syn-rift geometry of the strata does appear only in one-two particular locations of study area. From an author points of view there are two possible answers.

1. Different subsidence / rotation ratio along the fault length probably links to the strength of particular rocks.
2. Different sediment supply / subsidence ratio related to other possible sediment source along the fault, probably syn-deposition erosion of the crests of fault blocks.

To summarize interplay between tectonics and sedimentation with major consequence in syn-rift deposition, the main implications might be assigned as follows.

1. Syn-rift sedimentation yielding in different thickness distribution and non-paralel deposition of strata may provide useful tool in estimation of faulting time.
2. Tectonic influence on deposition is responsible for distribution of sedimentation patterns and facies associations and hence may be used in stratigraphy prediction.
3. Syn-rift deposition responsible for formation of rotated fault blocks is a first order control on distribution of stratigraphic traps in a basin.

9.6 Petroleum significance

It is generally agreed that tectonic influence on deposition exhibits first order control on forming significant and economically valuable hydrocarbon plays. First of all, extensional style of a basin appeared as rifting with major faults development provides the accommodation space to be filled by sediments coming into basins with rivers.

The problem of syn-rift architectural model with variety facies distribution and hence prediction of hydrocarbon play has been reviewed by Prosser (1993). Since the extension and rotation rates can vary as well as various non – marine and marine processes are involved in filling, the prediction of possible hydrocarbon bearing formation is primarily linked to the available subsurface data, 3-D seismic first of all.

It is believed that in the Late Jurassic sub-basins of the Northern North Sea there are two architectural patterns that emerge in the syn-rift sediments. They both occur mainly in hanging wall infill (Nøttvedt et al., 1995). The first unit might be described by basal and capping packages of sandstones, but with intervening shales. In the other hand, only basal sandstones and overlying shales are developed. The core and logging data acquired for wells penetrated Upper Ness formation within Gullfaks field in location next to the one examining suggest the first scenario representing variety alluvial successions of mudrocks, coal beds and fluvial sandstones, sandwiched between laterally persistent shallow marine sandstones (Ryseth, 2000).

The Brent Group been interpreted as wave dominated delta sediments was deposited during Middle Jurassic, from Early Bajocian to Early Bathonian, characterized by low subsidence rates making the majority of the Group’s strata almost parallel. The final architecture of the basin how it might be observed in recent three dimensional seismic data was affected by the rifting stage occurred probably in Late Jurassic and responsible for evolution of the rotated fault blocks (Yielding et al., 1992). However, the current study based on detailed seismic interpretation and fault displacement analysis argues the timing of those faults making it happened probably during the deposition of the Brent Group. From that point of view, the Upper Ness formation appearing to be strongly affected by syn-rift sedimentation might represent additional stratigraphic trap.

In terms of petroleum system Upper Ness formation representing the most lithostratigrafically variable stratigraphic unit of the Brent Group includes both organic rich black marine shales, some coal beds and fluvial channel sandstones that might be interpreted as a source and reservoir rocks. It is believed that the main source rock for black oil accumulations found in the Brent Group reservoirs are the organic rich marine shales of the Upper Jurassic Draupne or Kimmeridge clay formations with initial potential as high as 30 kg/tone. (Thomas,1985). The major faulting phase characterized by the significant rates of subsidence probably appeared during and just after the Upper Jurassic, was responsible for both structural trap formation and burial of source rock that generated hydrocarbons on a depth of 2-3 km, the “oil window” in Gullfaks area field is set up. However, in recent studies none of the organic rich shales deposited in particular Upper Ness age was considered as a source rock, and hence none of the local petroleum system within the Upper Ness formation was taken into account which, from author point of view, could represent additional reservoir volume with hydrocarbons filled.

The previous chapters and detailed analysis of 3-d seismic data together with suite of well logs have shown the existence of syn-rift deposition of Upper Ness Formation in distinct and relatively small areas of the Gullfaks filed where interplay between relative sea level and rates of subsidence caused deposition of wave dominated delta sediments (Upper Ness) on a crest of the fault block. That particular locality was estimated to have an area about 1.7 km^2 and is characterized by significant difference in thickness distribution, from 70 m on a foot wall scarp to 0-5 m on the fault block crest. In terms of the bulk volume it may represent approximately 60 x 10^6 cubic meters of different deposits of fluvial channels, organic rich shales and coal beds. From author’s point of view that distinct location and volume of rocks may represent the local petroleum system with essential elements as below.

1. Source rock is organic rich marine shales from both shallow and relatively deep marine environments deposited as consequences of change in regression/transgression cycles. It is generally agreed that Brent Group could be divided into 2 major sequences with main control in relative sea level change. The boundary distinguishing those sections is put exactly onto Upper Ness time when deposition of clastic wedge was associated with transgressive cycles (Graue et al., 1987). It is believed that anoxic conditions controlled by the marine environment could be described as essential element of forming ideal source rock. Consistent and relatively well known thermal and burial history of Upper Ness formation based on detailed study of cores, geochemistry analysis (Larter et al., 1992) and correlation within Northern North Sea allow to consider black marine shales as additional source rock.

2. Reservoir rocks within Upper Ness formation are might be represented by main sandstone bodies, generally characterized by sharp basal boundaries and an upward-fining grain-size motif. (Ryseth, 2000). General description of petrophysical characteristics of Upper Ness sandstones given by Moss (1993) suggests consistent from moderate to good reservoir qualities with average porosity values 10-15%. Despite that sandstones been interpreted as deltaic deposits, additionally an author would like to point out other probable source of sediments filling the available accommodation space during Upper Ness. Fig 9.5 proposes the significant erosion of fault crest majorly composed by the Lower Ness sediments and exposed under the sea level. Consequently the part of formation next to the fault block crest may contain sediments that been deposited as a result of erosion of Lower Ness formation. Additionally in terms of reservoir rock Upper Ness could exhibit a good reservoir quality due to deposition of coarse grained sediments that, as it believed, suggest the relatively high rates of subsidence comparing to sediment supply. To summarize, tectonic influence on deposition of Upper Ness caused probably the final depositional patterns with general trend of fining eastward and hence the improved reservoir quality towards the thickest part of the formation.
3. Seals and traps. Recent studies (Gluyas et al., 2004; Ryseth, 2000) suggest that majority of the oil within the East Shetland Basin was trapped in tilted fault blocks formed during Late Jurassic rifting. In the pre-rift section, oil is trapped in the sandstones of the Brent Group. With addition to structural traps formed by the tilted fault blocks, from an author's point of view, combination of syn-rift deposition with erosion of the fault crest may form stratigraphic traps as pinch-outs, economically profitable targets for drilling. In other words, the Upper Ness formation been deposited during relative sea level rise on a crest of the fault block might be described as stratigraphic sub trap with lateral seals formed by the marine shales from one side and sealing fault from another.

To summarize significance of the current project for both exploration for and production of hydrocarbons, the study area may represent additional petroleum system characterized by the variety of lithologies and sedimentation patterns forming and containing essential elements as source, reservoir and seal rocks making in attractive for further development. However, strong heterogeneity within Upper Ness formation may cause difficulties for flow patterns exhibiting barriers and limited volume of rocks with reduced permeability.

9.7 Proposed areas within the Gullfaks field for further studies on tectonic control deposition

Detailed analysis of seismic data acquired for the entire Gullfaks field suggests the probable existence of other strata within the Brent Group with fault control deposition. Fig. 9.7 shows the location of suggested for further studies areas. All those locations are related to the *4A* and *5* fault blocks with evidence for fault control deposition of the Lower Tarbert and the Upper Ness formations.

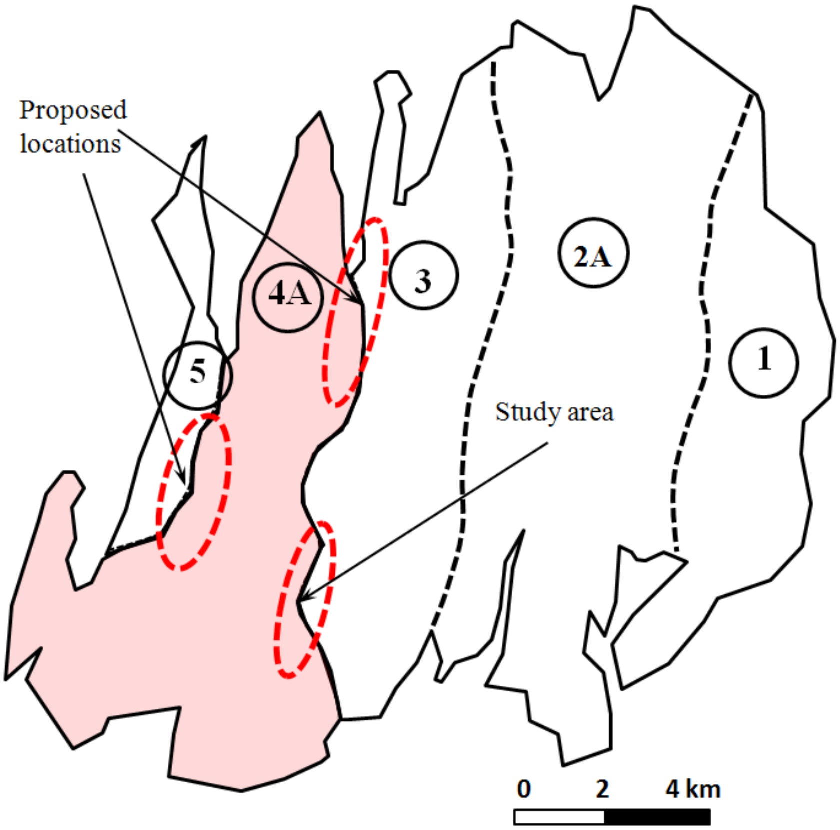


Fig.9.7. Proposed areas that exhibit tectonic influence on the deposition of the Brent Group members.

Conclusions

Available subsurface data analyzed and been used as input in key seismic – to – modeling software as Petrel ® and Landmark SeisWorks ® had been used to analyse distribution of the Brent Group sediments, Upper Ness in particular, in relation to tectonic control on deposition of Middle Jurassic sediments within the Gullfaks field. The field located in Shetland Basin was dominated by the long history of regional extensional style and subsidence distinguished by different magnitude and rates. Both thermal subsidence and climatic change are reflected in the distribution of facies patterns within the entire Brent Group section with major subdivision of Group into 2 main regressive-transgressive sections with a boundary in Upper Ness formation. Upper Ness formation as the most lithologically variable unit of the Brent Group had been interpreted as a complex of deltaic and coastal – plain sediments reflecting deposition during relative sea level rise (Yielding, 1992).

A part of the Gullfaks filed, with approximate area of 1 km^2 and limited by seismic lines 410 in the North and 365 in the South represent a fault-controlled deposition of Upper Ness resulting in thinning towards the fault crest and thickening towards footwall scarp. Isopaches and dip maps generated for both Upper Ness and Ness formations suggest an existence of paleo-island with approximate maximum height of 20 m above the sea level resulting from relatively small rate of subsidence (or local uplift) comparing to rest of the fault block. Fault-displacement analysis, throw- displacement relationships in particular, convinced the assumption of rapid increase in throw value in Ness formation along the length of the fault making existence of paleo-island consistently proved. Suggested in the thesis further approach should contribute to the statement of tectonic control deposition of the Brent Group. Since the lack of coring data and none of the wells been drilled in investigating in the thesis locality, an author proposing the detailed consideration of neighboring wells penetrated the same fault block. Core data, well logs, dip meter and GR in particular could be an additional tool for detailed description of syn-rift deposition of the Brent Group.

From petroleum system of view and possible further re-exploration of study area, syn-rift deposition of Upper Ness formation might be considered as diagenesis for representing additional local petroleum system. Organic rich marine shale, clastics from deltaic sediments and probable erosion from the crest of the exposed fault block might be considered as a source and reservoir rock respectively. Consequently additional stratigraphic traps been formed as a result of syn-tectonic deposition within rotated fault block might be an attractive target for drilling.

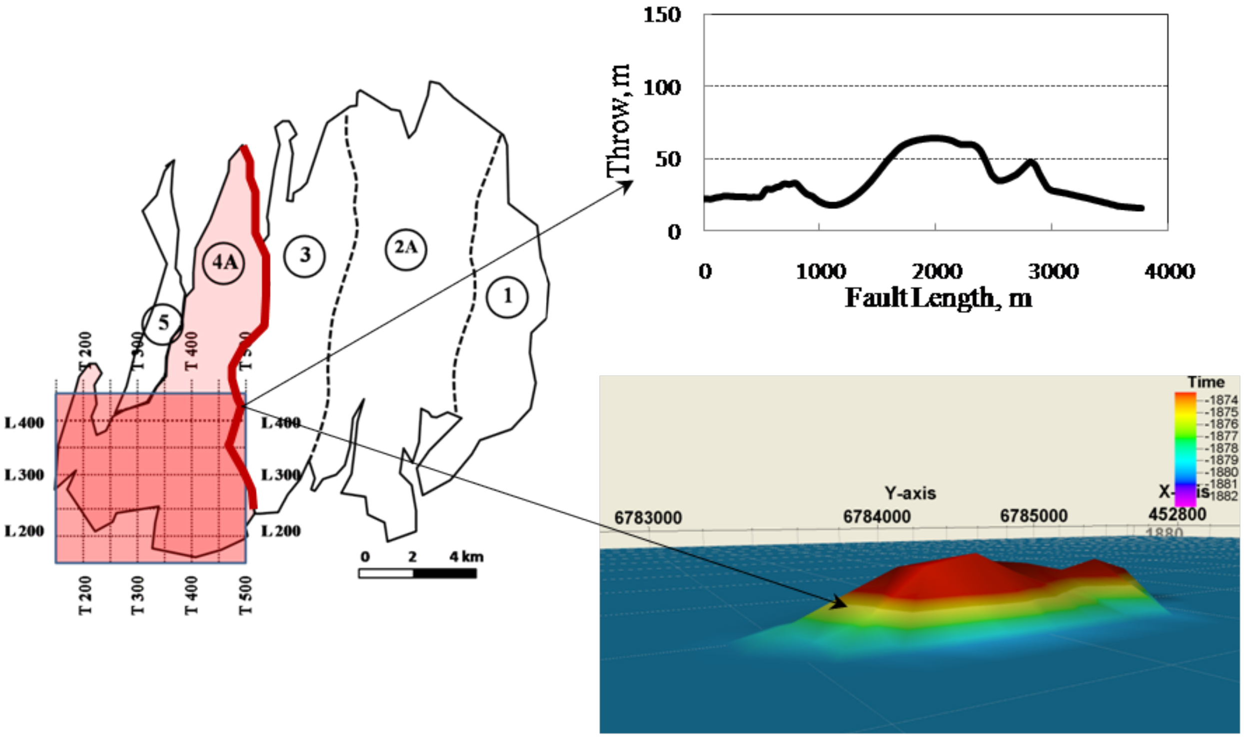


Fig.9.8 Summary of the project. The map view of the Gullfaks field with modified data set and investigated 4A rotated fault block .Fault- displacement diagram for the Main Fault 2 (shown in red on a map view) and paleo-island in the Lower Ness time.

List of figures

References

Arthur, B., F. Haakon, B. Eirik, and K. Trond Wannebo, 2008, Comprehensive Mini-Frac Testing in the Gullfaks Field as a Tool for characterisation of Reservoir Structure and Rock Mechanics, International Petroleum Technology Conference, Kuala Lumpur, Malaysia, International Petroleum Technology Conference.

Barnett, J. A. M., Mortimer,J., Rippon, J.,H., Walsh, J.J., Watterson, J., 1987, Displacement geometry in the volume containing a single normal fault.: American Association of Petroleum Geologists Bulletin, v. 71, p. 925-937.

Bjørlykke, K., Nedkvitne,Ramm, T.M., & Saigal, G.S., 1992, Diagenetic processes in the Brent Goup (Middle Jurassic) reservoirs of the North Sea: an overview Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 263-287.

Bowen, J. M., 1991, Introduction: In:Abbots, I.L. (ed.) United Kingdom Oil and Gas Fileds, 25 Years Commemorative Volime. Geological Society Memoir, v. 14, p. 9-20.

Cannon, S. J. C., Giles, M.R.,Whitaker, M.F.,Please P.M., & Martin, S.V. , 1992, A regional reassessment of the Brent Group, UK sector, North Sea: Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 81-107.

Dawers, N. H., Underhill, J.R., 2000, The role of fault interaction and linkage in controlling syn-rift stratigraphic sequences: Late Jurassic, Statfjord East Area, northern North Sea AAPG Bulletin, v. 84, p. 45-64.

Dickinson, W. R., 1974, Plate tectonics and sedimentation: Society of economic paleontologists and mineralogists, Special publication, v. 22, p. 1-22.

Evans, D., Graham, C., Armour A. and Bathurst, P (eds), 2003, The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea: Published by The Geological Society of London.

Fossen, H., 1989, Indication of transpressional tectonics in the Gullfaks oil-field, northern North Sea: Marine and Petroleum Geology, v. 6, p. 22-30.

Fossen, H., and J. Hesthammer, 2000, Possible absence of small faults in the Gullfaks Field, northern North Sea: implications for downscaling of faults in some porous sandstones: Journal of Structural Geology, v. 22, p. 851-863.

Fossen, H., and A. Rørnes, 1996, Properties of fault populations in the Gullfaks Field, northern North Sea: Journal of Structural Geology, v. 18, p. 179-190.

Galieva, E. P., 2009, Estimation of petroleum prospects of the Barents Sea basin on a sedimentation rate criterion: Petroleum geology: theory and application, v. 12, p. 1-3.

Glennie, K. W., 1998, Petroleum geology of the North Sea: basic concepts and recent advances: Oxford, Blackwell Science, XVI, 636 s. p.

Gluyas, J. G., and R. Swarbrick, 2004, Petroleum geoscience: Malden, Mass., Blackwell, XI, 359 s. p.

Godderij, R. R. G. G., A. G. Chessa, J. Bruining, and E. Kreft, 1995, Conditional Simulation of Subseismic Faults, SPE Annual Technical Conference and Exhibition, Dallas, Texas, 1995 Copyright 1995, Society of Petroleum Engineers, Inc.

Graue, E., Helland-Hansen, W., Johnsen, J., Lømo,L., Nøttvedt,A., Rønning, K., Ryseth, A. & Steel, R., 1987, Advance and retreat of Brent Delta System, Norwegian North Sea: In: Brooks, J & Gibbis, A.D. (eds) Petroleum Geology of North West Europe, p. 915-937.

Hafsteinn, A., S. Lars Kristian, and S. Odd Arve, 1999, The Gullfaks Field: Creating Value by means of a Multidisciplinary Reservoir Management Approach.

Helland-Hansen, W., Ashton, M., Lømo, L. & Steel, R, 1992, Advance and retreat of the Brent delta: recent contributions to the depositional model: Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 109-127.

Hesthammer, J., and H. Fossen, 2001, Structural core analysis from the Gullfaks area, northern North Sea: Marine and Petroleum Geology, v. 18, p. 411-439.

Kim, Y.-S., and D. J. Sanderson, 2005, The relationship between displacement and length of faults: a review: Earth-Science Reviews, v. 68, p. 317-334.

Le Dantec, N., L. J. Hogarth, N. W. Driscoll, J. M. Babcock, W. A. Barnhardt, and W. C. Schwab, 2003, Tectonic controls on nearshore sediment accumulation and submarine canyon morphology offshore La Jolla, Southern California: Marine Geology, v. 268, p. 115-128.

Marett, R., Allmendinger, R.W., 1991, Estimates of strain due to brittle faulting: Sampling of fault population: Journal of Structural Geology, v. 13, p. 735-738.

McKerrow, W. S., Mac Niocaill, C., Dewey, J.F., 2000, The Caledonian Orogeny redefined Journal of the Geological Society, v. 157, p. 1149-1154.

Miles, J. A., 1990, Secondary Migration Routes in the Brent Sandstones of the Viking Graben and East Shetland Basin: Evidence from Oil Residues and Subsurface Pressure Data: The American Association of Petroleum Geologists Bulletin, v. 74, p. 1718-1735.

Morley, C. K., Wonganan, N, 2000, Normal fault displacement characteristics, with particular reference to a sythetic transfer zones, Mae Moh mine, northern Thailand Basin Research, v. 12(3-4), p. 307-327.

Morton, A. C., Haszedine, L.M., Giles, M.R., & Brown, S, 1992, Geology of the Brent Group: Introduction: Geological society Special Publication, v. 61, p. 1-2.

Moss, B., 1993, The petrophysical characteristics of the Brent sandstones. : In: Morton, A.C., Haszeldine, R.S., Giles, M.R. and Brown, S (eds.), Geology of the Brent Group, Geological Society Special Publication, v. 61, p. 471-496.

Muraoka, H., and H. Kamata, 1983, Displacement distribution along minor fault traces: Journal of Structural Geology, v. 5, p. 483-495.

Nicol, A., Walsh, J.J., Watterson, J.& Gillespie, P.A., 1996, Fault size distribution - are they really power law?: Journal of Structural Geology, v. 18, p. 191-197.

Nottvedt, A., R. H. Gabrielsen, and R. J. Steel, 1995, Tectonostratigraphy and sedimentary architecture of rift basins, with reference to the northern North Sea: Marine and Petroleum Geology, v. 12, p. 881-901.

Petterson, O., Storli, A., Ljosland, E., Nygaard, O., Massie,I., Carlsen, H., 1992, The Gullfaks field: Chapter 27: In: M54: Giant Oil and Gas Fields of the Decade 1978-1988, p. 429-446.

Prosser, S., 1993, Rift-related depositional systems and thier seismic expression.: In:G.D. Williams and A. Dobb (eds.). Tectonics and Seismic Sequence Stratigraphy, Special Publications of the Geological Society of London, v. 71, p. 35-66.

Ravnås, R., and R. J. Steel, 1997, Contrasting styles of Late Jurassic syn-rift turbidite sedimentation: a comparative study of the Magnus and Oseberg areas, northern North Sea: Marine and Petroleum Geology, v. 14, p. 417-449.

Richards, P. C., 1992, An introduction to the Brent Group: a literature review Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 15-26.

Ryseth, A., 2000, Differential subsidence in the Ness Formation (Bajocian), Oseberg area, northern North Sea: facies variation, accommodation space development and sequence stratigraphy in a deltaic distributary system.: Norsk Geologisk Tidsskrift, v. 80, p. 9-26.

Ryseth, A. F., H., 1995, Differentiation of incised valley systems from mobile streams: some examples from the Oseberg Field, Norwegian North Sea.: In: Steel, R.J., Felt, V.L., Johannessen, E.P. & Matheiu, C (eds.): Sequence Stratigraphy on the Northwest European margin. NPF Special Publication, v. 5, p. 51-73.

Stattegger, M., Morton, A.C., 1992, Statistical analysis of garnet compositions and lithostratigraphic correlation: Brent Group sandstones of the Oseberg Filed, northern North Sea: Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 245-262.

Thomas, M., 1986, Diagenetic sequences and K/Ar dating in Jurassic sandstones, central Viking Graben: effects on reservoir properties. : Clay minerals v. 21, p. 695-710.

Tollefsen, S., E. Graue, and S. Svinddal, 1992, The Gullfaks Field Development: Challenges and Perspectives, European Petroleum Conference, Cannes, France, 1992 Copyright 1992, Society of Petroleum Engineers, Inc.

Underhill, H. D. D. J. R., 2000, The role of interaction and linkage in controlling synrift stratigrahic sequences: Late Jurassic, Statfjord East Area, Northern North Sea.: AAPG Bulletin, v. 84, p. 45-64.

Walsh, J. J., Watterson, J., 1988, Analysis of the relationship between displacements and dimensions of faults: Journal of Structural Geology, v. 10, p. 317-328.

Watterson, J., 1986, Fault dimensions, displacement and growth: Pure and Applied Geophysics, v. 124.

Yielding, G., Badley, M.E.& Roberts, A.M., 1992, The structural evolution of the Brent Province: Geology of the Brent Group. Geological Society Special Publication, v. 61, p. 27-43.