PS 3-D Structural Evolution and Analysis of Complex Mesozoic Grabens in Guinevere Field UK Southern North Sea*

Aji Kyari[1] and Chris Elders[1]

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[1]Earth Sciences, Royal Holloway, London, United Kingdom (a.kyari@es.rhul.ac.uk)

Abstract

The Guinevere field in the UK Southern North Sea is characterized by the presence of complex Mesozoic grabens trending in the NW-SE. A prominent feature of these grabens is the presence of a Lower Triassic Separation Zone (LTSZ), which is characterized by the absence of the Lower Triassic Bunter Group (Bunter Shale and Sandstone Formations). These grabens are bounded by basinward and landward listric growth faults which detach on the Permian Zechstein and Triassic Haisborough Groups.

Graben1 shows crestal collapse structure containing series of synthetic and antithetic faults, which probably developed as a result of accommodating extension on the listric growth faults. Graben 2 on the other hand developed from an asymmetric half graben to a full graben with no crestal collapse structures. An array of domino style faults with an oblique extensional direction (ENE) relative to the graben bounding faults (NW-SE) detaching on the Triassic Haisborough Group developed during the Jurassic extension. The change in direction of these domino faults is attributed to a reorientation of the stress field.

A 3-D structural evolution model is proposed for the formation of these grabens, the suggested mechanisms are salt tectonics and extensional faulting utilizing multiple detachment layers of the Permian Zechstein and Triassic Haisborough Group in two different phases of extension. Listric extensional faults cut and caused the rotation of the hanging wall units within the Upper Triassic sequences and detached on the Upper Permian Zechstein. The subsequent development of an antithetic listric fault detaching on the inclined Haisborough Group causes the separation zone to form during the Lower Jurassic.

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Aji Kyari & Chris Elders
Department of Earth Sciences, Royal Holloway University of London
a.kyari@es.rhul.ac.uk and c.elders@es.rhul.ac.uk

1 Introduction

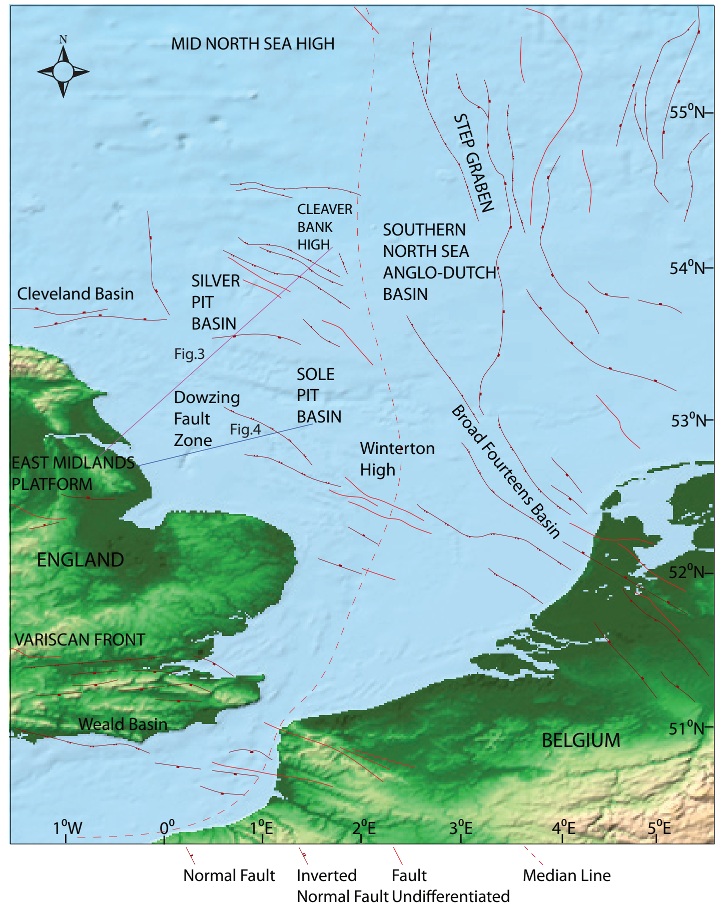

Figure 1. Structural Setting of the Southern North Sea .

Introduction

The Southern North Sea basin lies between England and Netherlands (Fig.1) and is characterized by extension and inversion in which block faulted Carboniferous and Rotliegend sequences are separated by ductile Zechstein salt from Mesozoic sequences that locally show complex deformation. A common feature of this is grabens which are marked by the absence of the Lower Triassic (Lower Bacton or Bunter Group) or Lower Triassic Seperation Zones (LTSZ) at their centres. (Fig. 2b) . The entire Bacton Group is absent in many places in the Southern North Sea; Camelot Field, (Holmes, 1991 and Karasek and Hunt 2003), Pickerill Field (Werngren et al., 2003), and in Guinevere Field (Lappin et al., 2003.). This has been a problem for interpretation of seismic data. The objective of this poster is to propose a model for the evolution of these complex Mesozoic grabens where most of the Lower Triassic Separation Zones (LTSZ) are located.

Study Area

The study area is Guinevere Field located 43 miles (70km) east of the Humber Estuary and 31 miles (50km) north of the Norfolk Coast within Block 48/17b (Fig.2). The field is a NW-SE trending fault block that is 3.4 miles (5.5km) long and 1mile (1.6km) wide and lies in water depth of 88ft (27m) (Lappin et al 2003). The Field is located within the footwall of the Dowsing Fault Zone on the western flank of the Sole Pit Basin (Fig. 2). It is a NW-SE trending extensional fault block at Rotliegend level.

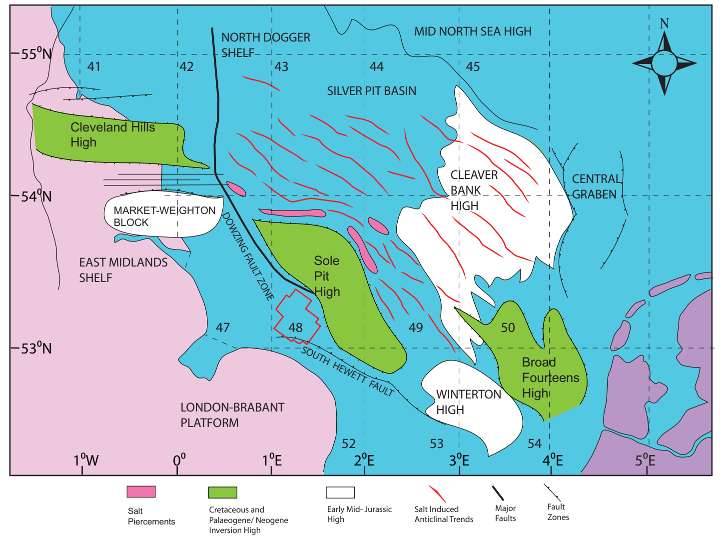

Figure 2a. Mega tectonic map of the Southern North Sea showing the location of Guinevere field and the 3D seismic survey(in red box) with the structural features Modified from Van Hoorn 1987.

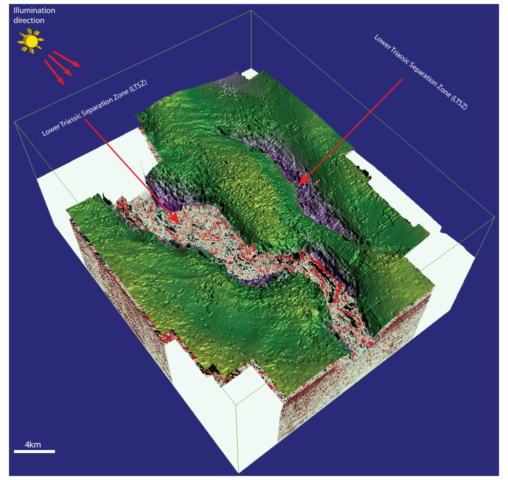

Figure 2b. Base Haisborough 3D perspective structure showing Lower Triassic SeparationZones (LTSZ) in Guinevere Fueld

2 Regional Settings

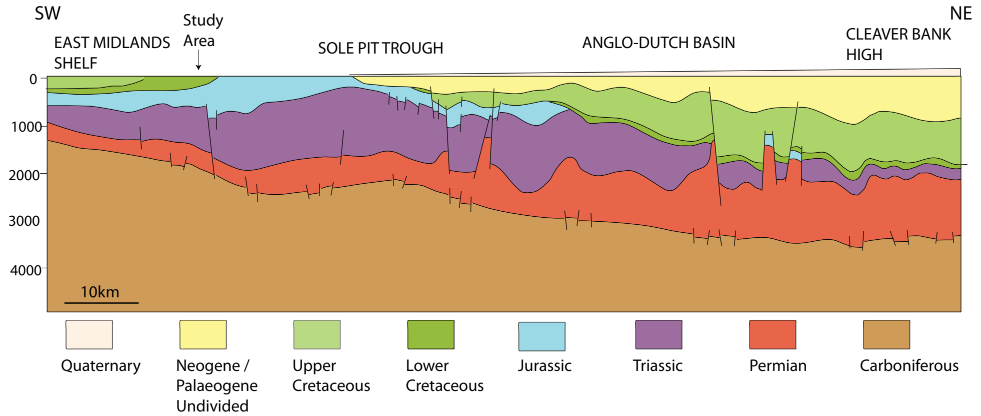

Figure 3. Regional cross section across the Southern North Sea after Cameron et al.,1992 see (Fig. 1) for line location.

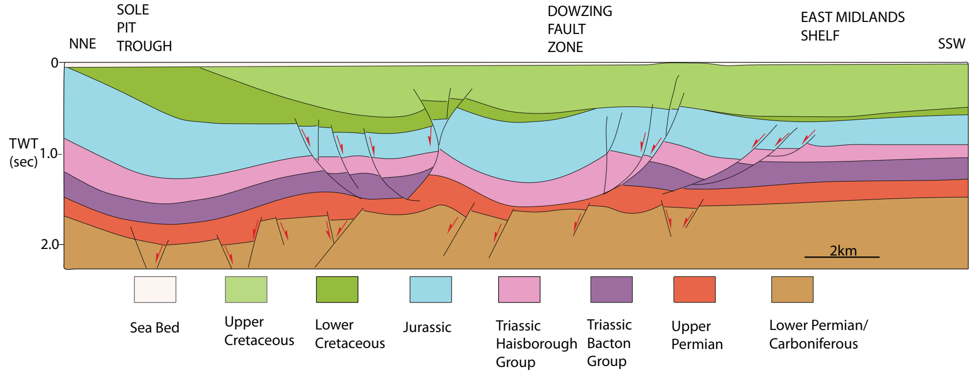

Figure 4. A complex structural and stratigraphic relationship across most part of the Southern North Sea after Cameron et al.,1992 see (Fig. 1) for line location.

Regional Settings

The Southern North Sea consists of four major fault zones; Dowzing Fault Zone (DFZ), Sole Pit Basin, Silver Pit Basin and the Cleaver Bank High (Fig. 1). The extensional and compressional features in the Southern North Sea are preserved along these fault zones. The present structural framework of the Southern North Sea is represented by late Jurassic to early Cretaceous extensional tectonics along these fault zones. Differential subsidence of the Sole Pit Basin was emphasised by the development of growth faults along its western margin (Cameron et al., 1992).

A regional cross-section across the Dowsing Fault Zone (Fig. 3) shows that thicker sediment acumulated on the basin centres and around the extensional fault zones. However closer to the basin margin there are major unconformities in the stratigraphic sequences associated with decrease in sediment thickness in the Sole Pit Trough (Fig. 3). This occurred as result of compression during the late Cretaceous and early Cenozoic which lead to the inversion, uplift and erosion of the Sole Pit Basin. A typical structural complexity associated with the stratigraphic relationships within the Dowzing Fault Zone is illustrated in Fig. 4. The prominent feature to be noticed in the cross section is the missing Lower Bacton Group within the major graben. The Mesozoic sediments within the graben are dissected by system of en–enchelon asymmetric grabens that trend north–west to south–east (Fig. 4); these probably started to develop during the late Triassic in the Dowsing Fault Zone. Each of the graben is bounded by listric normal faults which sole out or detach in the Upper Permian halites (Fig. 4); halokinetic deformation of these effectively decoupled the faulting in the Mesozoic cover from contemporary deformation of the pre-Permian basement.

The presence of the complex Mesozoic graben and Lower Triassic Separation Zone (LTSZ) in the Guinevere Field is illustrated in Figure 5 (a-c), below . A seismic traverse passing through five wells shows two grabens (1 and 2) with Lower Triassic Separation Zones at their centres (Fig.5a). A similar feature is observed in well 48/18-11 above the Permian Zechstein highligted in red box (Fig. 5b). A 3D perspective view of interpreted Base Haisborough also shows the separation zones in Fig. 2b.

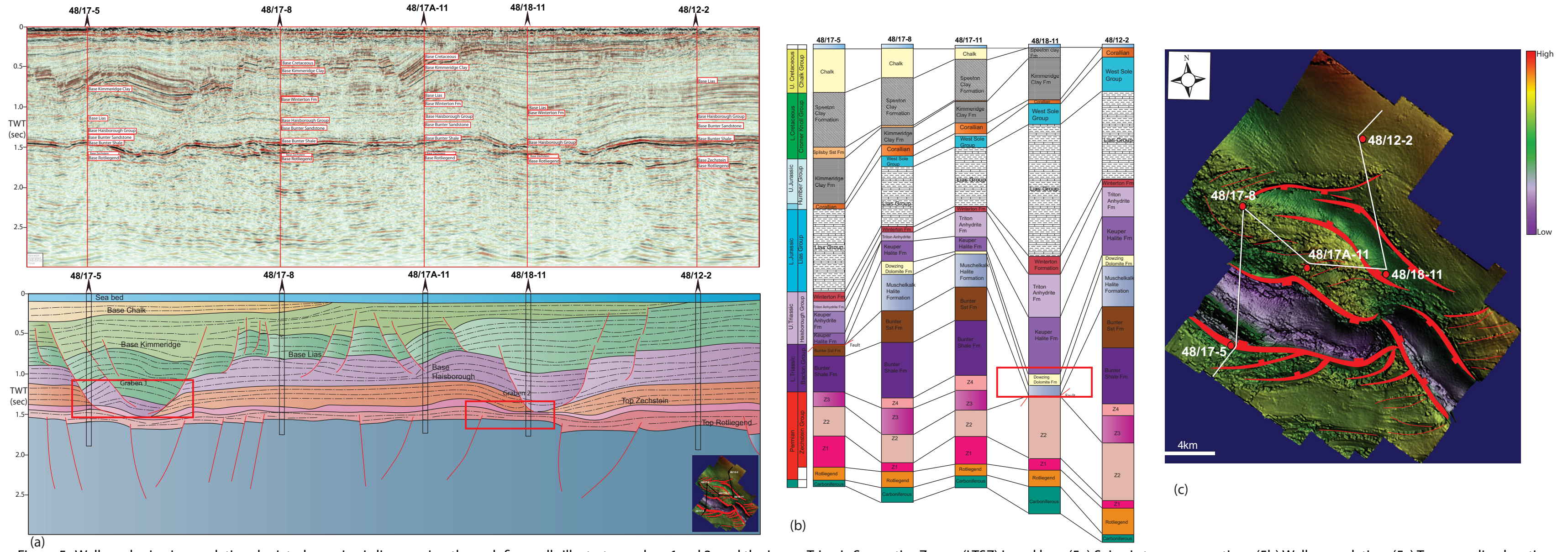

Figure 5. Wells and seismic correlation depicted on seismic line passing through five wells illustrates graben 1and 2, and the Lower Triassic SeparationZones (LTSZ) in red box (5a) Seismic tranverse section (5b) Wells correlation (5c) Tranverse line location

3 Tectono-Stratigraphy and Seismic Stratigraphy

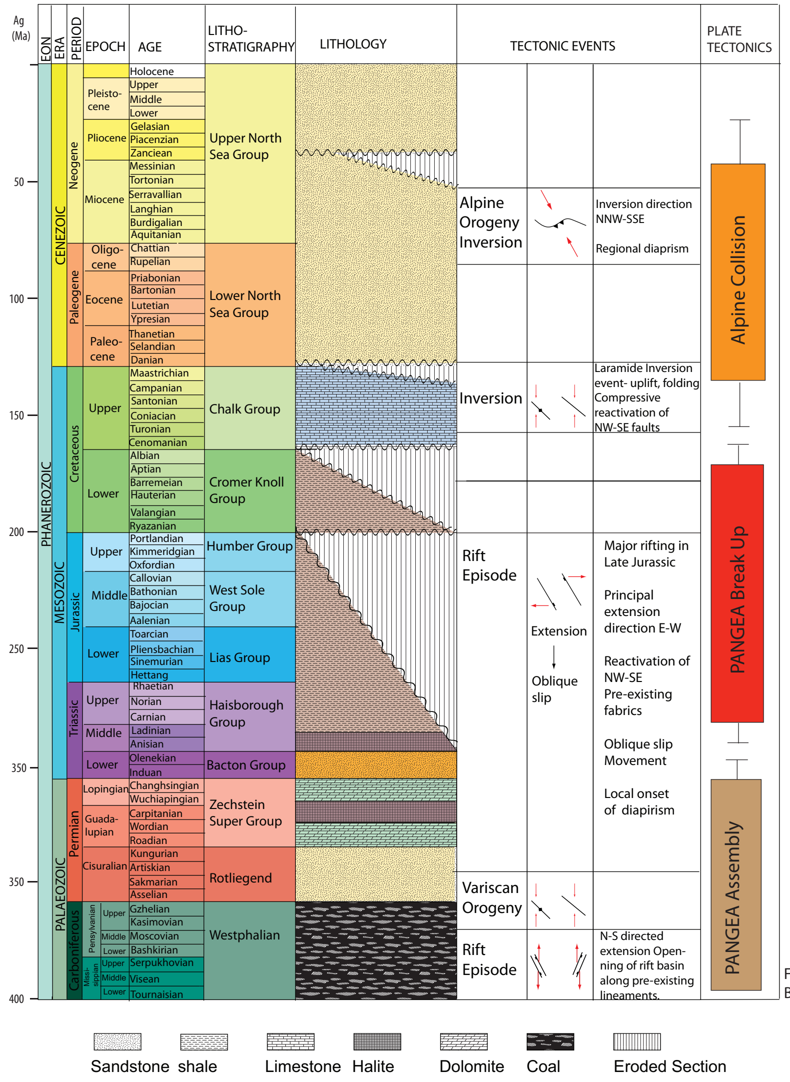

Figure 6. Tectonostratigraphic chart of the Southern North Sea compiled from Van Hoorn,1987, Badley et al.,1989 ,Arthur,1993, Hughes and Davison,1993, Birrel and Courtier 1999 .

Tectono-Stratigraphy

The tectonic events that affected the North Sea can be summarised in to four main phases, these are; Caledonian, Variscan, Kimmerian and the Alpine phases. The Caledonian phase occurred during Cambrian to Silurian as a result of the collision between Laurentia, Baltica and Avalonia during the Silesian. This event was followed by the Variscan phase which occurred during the late Paleozoic from late Devonian times to the end of the Permian and involved the amalgamation of Gondwanaland and Laurussia resulting in the formation of a new super continent, Pangae. The Kimmerian phase marked the beginning of the breakup of Pangaea, and is a major phase of rifting in the North Sea. The phase lasted for most of the Mesozoic and stretches from the Late Triassic to the Early Cretaceous . In the late Cretaceous the Alpine phase commenced and primarily reactivated and inverted old faults.

In the Southern North Sea, the major tectonics events include extension in the Late Triassic- Early Jurassic, subsidence in the Middle Jurassic- Early Cretaceous and Inversion post -Late Cretaceous (Fig. 6). The extension during the Late Triassic to early Jurassic is attributed to enhanced subsidence of the Silver Pit Basin and that of Sole Pit Trough (Moscariello, 2003). The subsidence in the Jurassic was fundamentally controlled by continued extension on the Dowsing Fault Zone (DFZ) with the distribution of sediments increasingly affected by salt tectonics. The compression during the late Cretaceous and early Cenozoic results in the development of large anticlinal structures in the post-Permian sequence with a dominant NW-SE structural trend. T

he geological succession of the Southern North Sea begins with the Carboniferous Westphalian strata which was followed by the basin infill of Permian sediments. These were deposited in a foreland basin setting with a semi arid to arid environment resulting in cyclic deposition of thick Zechstein salt of up to 2000m in the Upper Permian (Cameron et al., 1992). The Permian Zechstein and Triassic Haisborough group salt (Fig. 6) formed major detachment layers in the region causing post-depositional halokinetic deformation of the overburden. The succession runs through up to the Quaternary. The detailed stratigraphy is summarised in Figure 6.

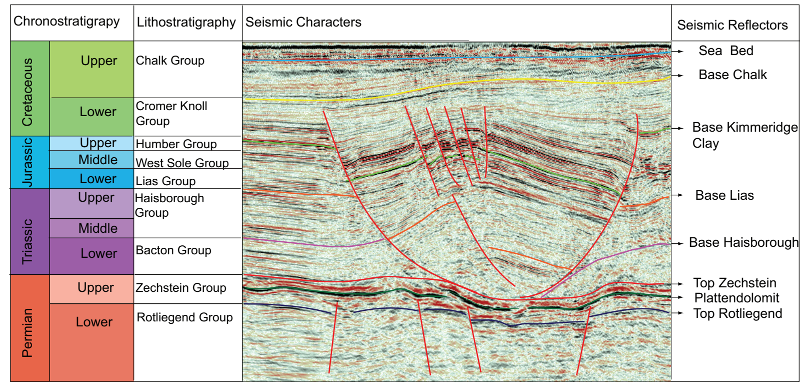

Figure 7. Seismic horizons picked and stratigraphy of Guinevere field,Southern North Sea.

Seismic Stratigraphy

The seismic stratigraphy of Guinevere Field (Figure 7)ranges from Lower Permian to the Cretaceous. The 3D seismic data set generally has good resolution above 1.75 TWT (sec). A total of seven key horizons were picked and interpreted. These are Top Rotliegend interpreted to demostrate the pattern and structural orientation at Sub- salt level, Top Zechstein which serves as major detachment layer that decouples both Basement and cover sequences, Base Haisborough which is a key horizon that is missing within grabens and indicates the Lower Triassic Separation Zones (LTSZ) described in figures 2b, 5a and 5b. Base Lias was interpreted because it was a syn kinematic sequence that serves as a second detachment layer. Base Kimmeridge was interpreted to demonstrate a major syn kinematic phase that provides evidence for the Jurassic extension. Base Chalk was interpreted to illustrate timing of fault activity and the understanding of the post kinematic activity within the complex Mesozoic graben.

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4 Guinerevere Field Structural Styles

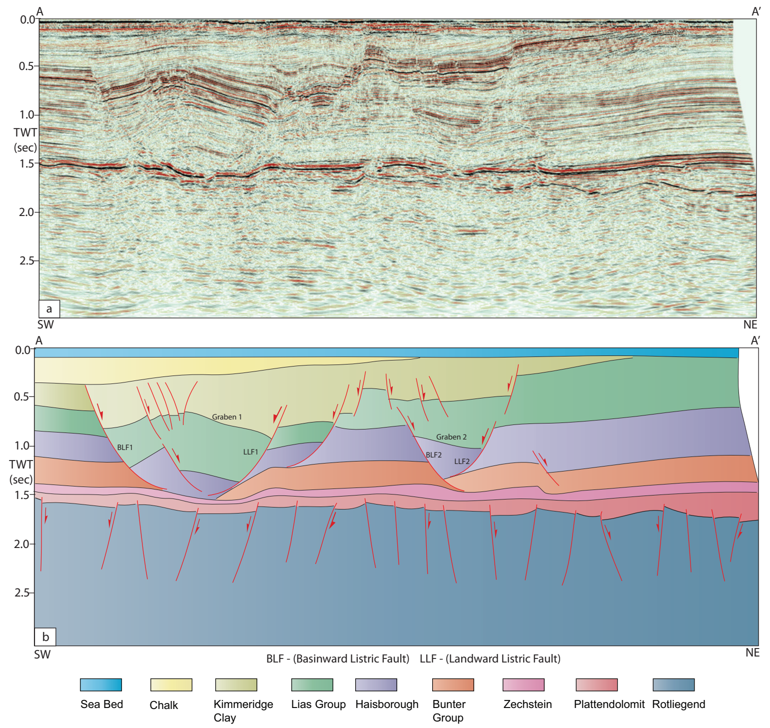

Figure 8. (a) Uninterpreted and (b) interpreted 3D Seismic section A-A′ trending SW-NE from the Guinevere field 3D survey showing the main structural features see Figure 10 for line location.

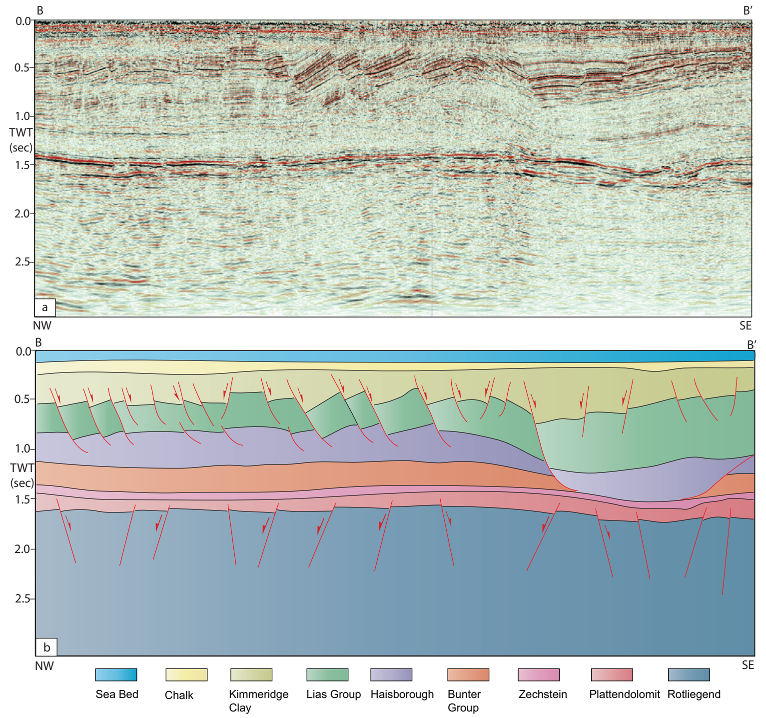

Figure 9. (a) Uninterpreted and (b) interpreted 3D Seismic section B-B′ trending NW-SE from the Guinevere field 3D survey showing the main structural features see Figure 10 for line location.

Planar domino fault below salt

The Guinevere field consists of two salt detachment layers of the Upper Triassic Haisborough and Upper Permian Zechstein Group. Beneath the Zechstein detachment, faults at Top Rotliegend are tilted and rotated, dominantly planar domino style with small extensional separations. These small segmented faults are separated from the overlying post salt structures by decollement via the Zechstein. The vertical downward extent of these faults to basement level are poorly defined and constrained due to poor resolution of the seismic beyond the Rotliegend (Fig. 8a and 9a). Most of these faults are trending in NW-SE directions (Fig. 11) which conforms to the structural grain of the basin; however some of these faults trend in the E-W direction indicative of reverse movements. The seismic sections (Fig. 8b) illustrates some of these reverse movement on the extensional fault blocks at the Top Rotliegend level.

Listic faults defining graben systems

Listric faults are curved normal faults which occur in extension zones where the fault surface is concave upwards and its dip decreases with depth. Its hanging wall block may either rotate and slide along the fault plane or may pull away from main fault. Deformation in the hanging wall is characterized by the presence of roll over anticlines and occasionally with associated crestal collapse structures (Fig. 8b) .

There are two grabens (graben1 and 2), which are bounded by two large listric growth faults. Graben 1 is bounded by basinward listric fault1 (BLF1) and landward listric fault1 (LLF1) and graben 2 is bounded by basinward listric fault 2 (BLF2) and landward listric fault2 (LLF2), these faults are the major listirc faults within the Guinevere field. Three of the faults (BLF1, LLF1 and BLF2) detach on the Upper Zechstein while LLF2 detaches on the Upper Triassic Haisborough Group where it has been rotated (Fig. 8b). These faults are steep at the top and they are curved, bend and flatten at the base with maximum displacements recorded at its centre.

Faults (listric and planar) detaching on Haisborough

The Upper Triassic Haisborough Group serves as the second detachment layer within the Guinevere field and permits listric faulting of the Upper Triassic/Jurassic sequence with detachment above the Lower Triassic Bacton Group. The 3D seismic sections in figure 8b, shows listric and planar growth faults off setting Kimmeridge and Lias Group sequences and detaching on the Upper Triassic Hiasborough group. Some of these faults are segmented growth fault with small displacements which are probably associated with the Jurassic extension. They trend in different directions (ENE) relative to the graben2 bounding landward listric fault (LLF2) which trends in NW-SE direction. The graben2 bounding landward listric fault (LLF2) and the series of listric and planar faults cutting the Kimmeridge and the Lias Group detach within the Haisborough

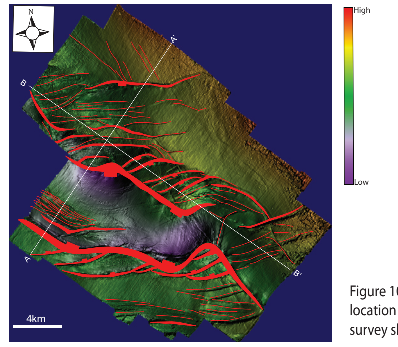

Figure 10. Base Kimmeridge structure map showing location 3D seismic lines from the Guinevere field 3D survey showing Line A-A′ (SW-NE) and Line B-B′ (NW-SE).

5 Structural Variations

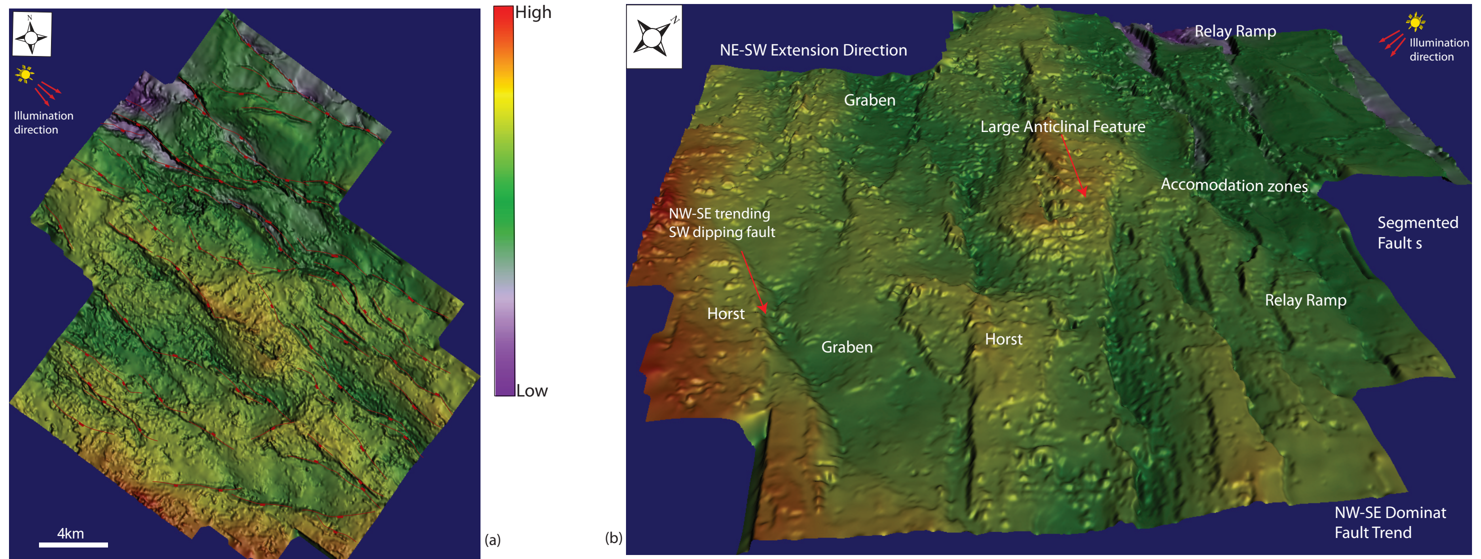

Figure 11. (a) Shaded relief and (b) 3D perspective view of Top Rotliegend time structure map with fault interpretation.

Top Rotliegend

The Top Rotliegend in the Guinevere field represents a sub-salt structural configuration of the basin. The structure map (Fig. 11) displays a series of small segmented plannar extensional faults trending in NW-SE direction some of which may have been initiated in the Carboniferous and probably reactivated during the Mesozoic. In seismic sections (Fig. 8b and 9b) the faults are generally plannar extensional faults with small separations that mostly lie nearly parallel to each other. These faults have low displacement, and underlie some prominent Mesozoic structures but do not directly link with them (Fig.8b and 9b). The faults were detached from the cover faults and supra salt structures by the Permian Zechstein decollement. The series of tilted and rotated fault blocks results in the formation host and grabens on the Rotliegend structure map.

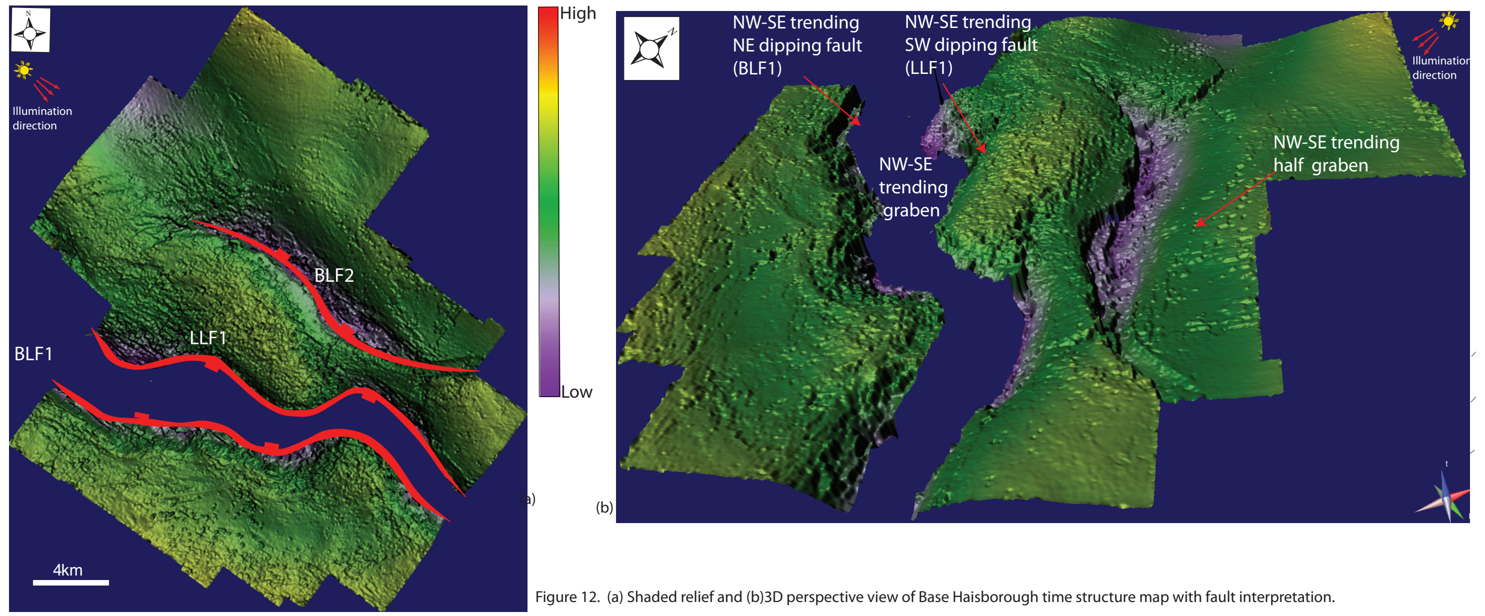

Figure 12. (a) Shaded relief and (b)3D perspective view of Base Haisborough time structure map with fault interpretation.

Base Haisborough

The Base Haisborough structure map (Fig.12) shows three major faults ; basinward listric fault (BLF1) and landward listric fault (LLF1) trending in NW-SE which cut and offset the Jurassic sequences at high and low angles respectively (Fig. 8b). A second basinward listric fault (BLF2) cut and offset the sequence forming an asymmetric half graben in the NE of the survey area and also trends NW-SE . Seismic sections illustrates that these fault (BLF1, LLF1 and BLF2) do not root downward and link with the Permian fault system at the Top Rotliegend but detach on the Upper Permian Zechstein. It also demonstrate the presence of the Lower Triassic Separation Zones (LTSZ) characterised by the absence of the Bunter Group (Bunter shale and Bunter sandstone, located within graben1.

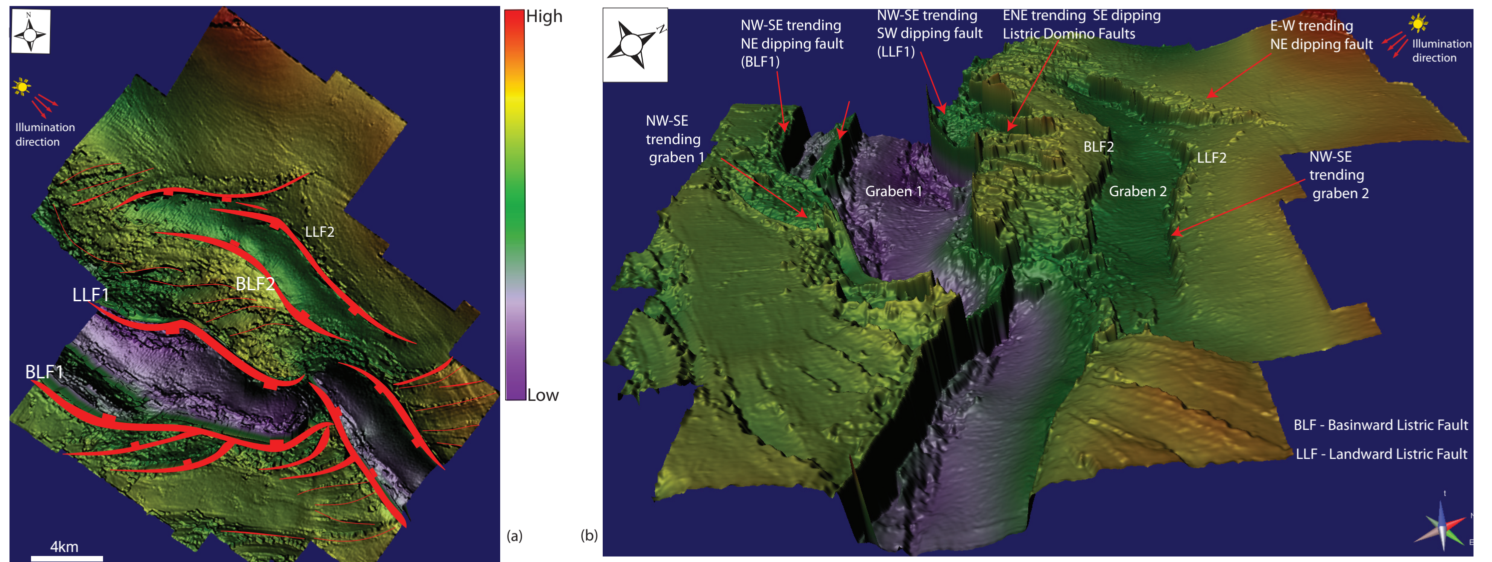

Figure 13. (a) Shaded relief and (b) 3D perspective view of Base Lias time structure map with fault interpretation.

Base Lias

The Base Lias structure map shows four major faults ; basinward listric fault (BLF1) and landward listric fault (LLF1) bounding graben 1 and basinward listric fault (BLF2) and landward listric fault (LLF2) bounding graben 2 all trending in NW-SE. These faults cut and offset the Jurassic sequences at high and low respectively (Fig.8b,15,16,and 17). It also shows a different oriented fault located at the N margin of graben 2. The surface also shows the presence ENE trending faults located between LLF1 and BLF2 and few others towards the S and SE. These ENE faults are small listric to plannar isolated faults that offset Jurassic sediments and detached on the Upper Haisborough.

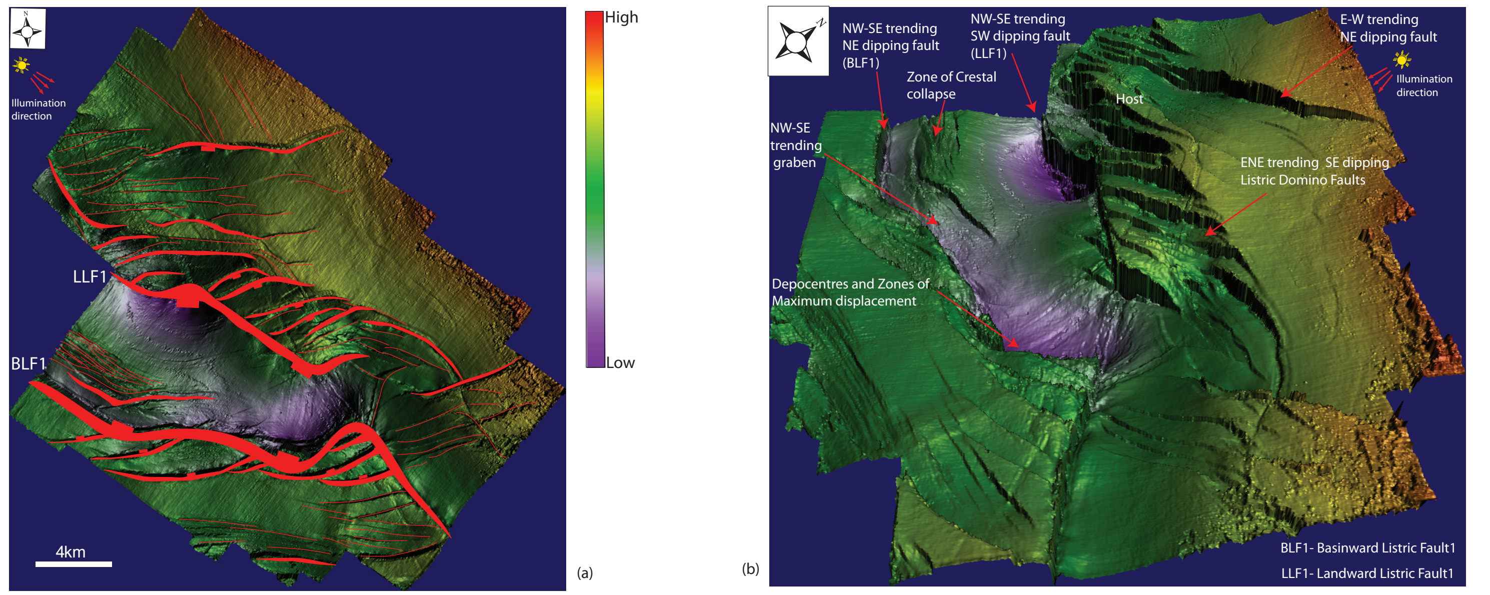

Figure 14. (a) Shaded relief and (b) 3D perspective view of Base Kimmeridge time structure map with fault interpretation.

Base Kimmeridge

The Base Kimmeridge structure map (Fig. 14), represent structural style of a late supra salt sequences in the Guinevere field . It displays graben at its centre trending NW-SE bounded by listric growth faults BLF1 and LLF1. These faults dip in the opposite direction to each other with the BLF1 dipping NE and LLF1 dipping SW . The graben centre shows series of synthetic and antithetic faults located at the crestal collapse zone, the general orientation of these faults are NW-SE directions. it indicates that graben 2 only has expression at Base Lias Lower Jurassic level (Fig. 13). The map also illustrates, the development of series small ENE trending faults . This array of domino faults have soft linkage with the graben bounding faults . The curvature of the ENE implies that it is controlled by underlying faults at Base Lias surface which were not reactivated. The graben centre shows series of synthetic and antithetic faults located at the crestal collapse zone, the general orientation of these faults are NW-SE directions. These faults developed as a result of accommodating net extension induced by folding due to roll over on graben bounding listric faults (Fig. 8b,15,16, and 17).

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6 Graben Structure and Along Strike Variations

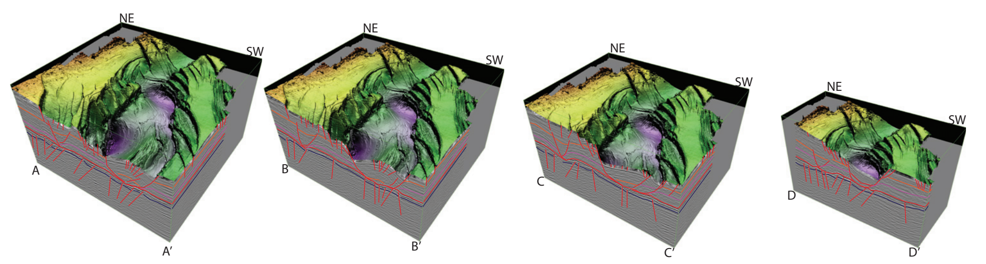

Figure 15 . 3D cube seismic volume cut illustrating internal geometry and along strike variations of both graben 1 and 2 at Base Kimmeridge level .

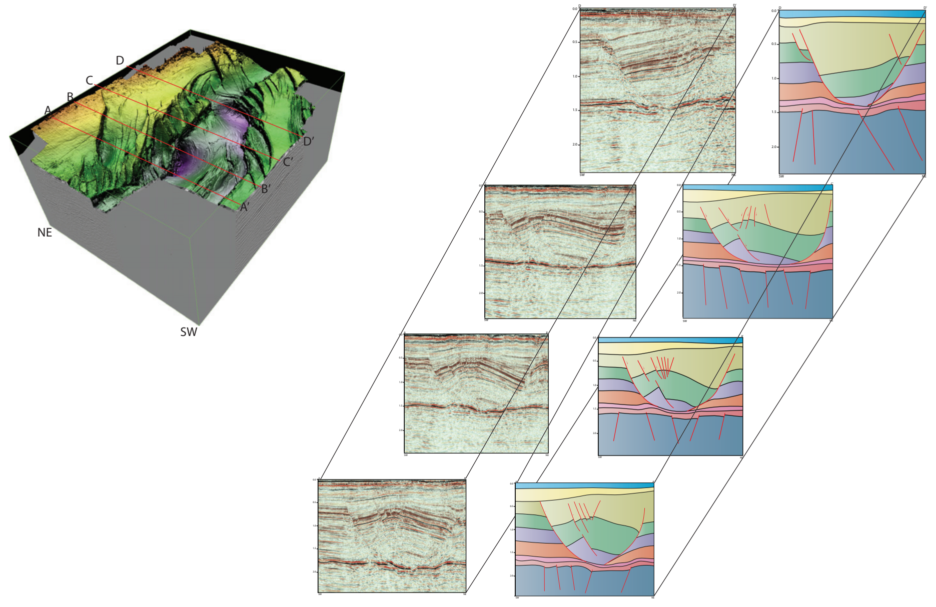

Figure 16 . (a) Uninterpreted and (b) Interpreted seismic section illustrating along strike variations of graben 1.

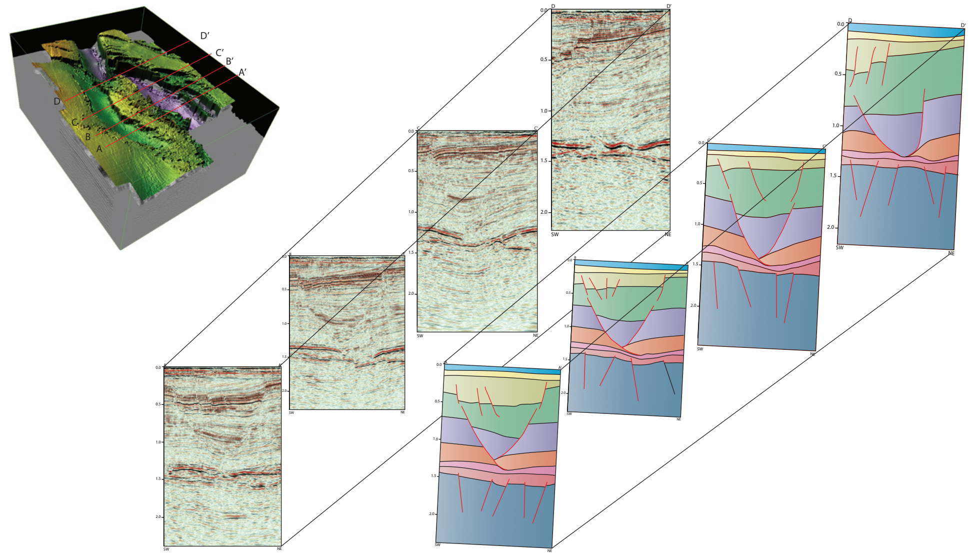

Figure 17 . (a) Uninterpreted and (b) Interpreted seismic section illustrating along strike variations of graben 2.

Graben structure and internal geometry

The seismic volume cut in Figure15 displays the internal geometry of graben 1 and 2 along, with significant variations apparent along strike of these structure. It is evident form the geometry that the basinward and lanwdward fault cut Triassic and Jurassic sequences at high and low angles respectively (Fig. 15). Graben 1 shows double roll overs in section A-A′ and B-B′ with associated crestal collapse structures while graben two did not record such features. The interaction between graben 2 bounding fault (BLF2) and overlying faults at Base Kimmeridge show significant variation from nearly no linkage (Fig. 15 section A-A′) to almost hard linkage in section C-C′.

Graben 1- along strike variations and vertical extent

Graben1 is located in the NW part of the survey, it bounded by basinward listric fault1 (BLF1) and landward listric fault1 (LLF1). T he hanging wall geometry of this graben indicates the presence of roll over anticline with a necessary crestal collapse structure illustrated in section A-A′ - C-C′. (Fig.16) It consists of series of synthetic and antithetic faults detaching within the graben (section A-A′ and C-C′). The presence of major depocentres are displayed in section B-B′ and D-D. In all the sections the basinward and landward faults cut and offset the sequences at high and low angles and detach on the Upper Permian Zechstein.

Graben 2- along strike variations and vertical extent

Graben 2 is located NE of the graben1, it is bounded by basinward listric fault2 (BLF2) which cut and offset the sequences at high angle and detached on the Upper Permian Zechstein and Landward listric fault2 (LLF2) which cut and offset the sequence at low angle and detach on the Upper Triassic Haisborough Group where it is rotated.
The graben changes from an asymmetric half graben to a full symmetric graben; its centre is filled with the Lias and Haisborough Groups.

Along strike of graben 2 (Fig.17) the Lias Group and Haisborough has greater thickness more at the basin centre (Section C-C and D-D′) relative to the other parts of the basin. The vertical extent of graben 2 terminates within the Middle Jurassic sequences. In comparison to the graben1, the centre of graben 2 (Fig.17) does not record roll over anticlines, crestal collapse structures and inversion features.

7 Evolution, Growth and Timing of Fault Activity

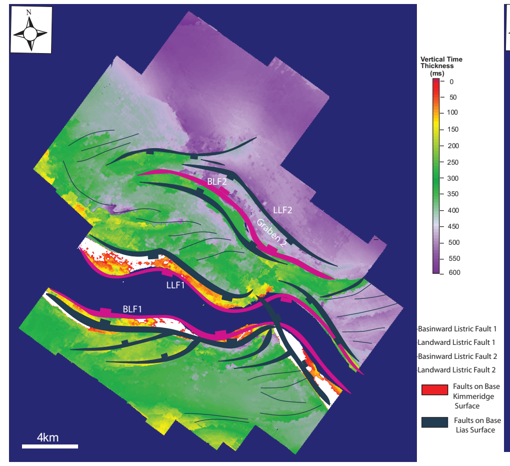

Figure 18. Base Haisborough -Base Lias interval vertical time thickness map with fault interpretation.

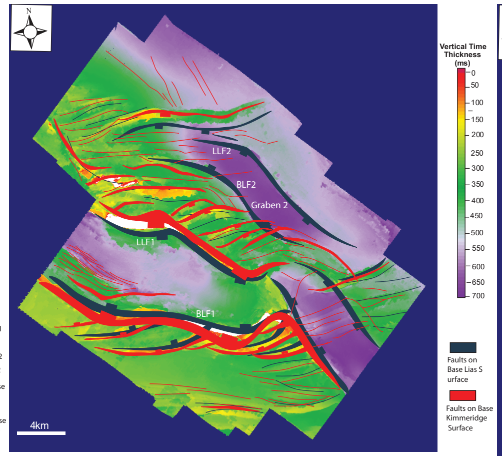

Figure 19. Base Lias - Base Kimmeridge interval vertical time thickness with fault interpretations.

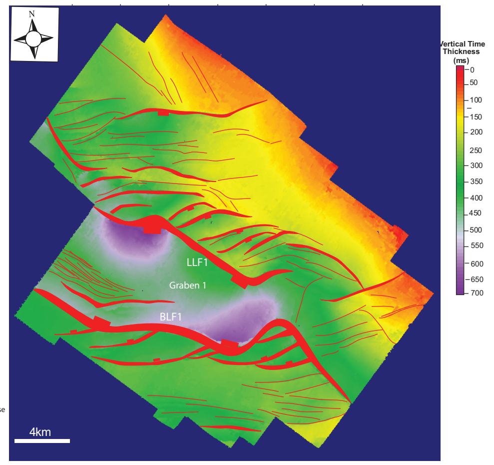

Figure 20. Base Kimmeridge- Sea Bed vertical time thickness map Base Kimmeridge fault interpretation.

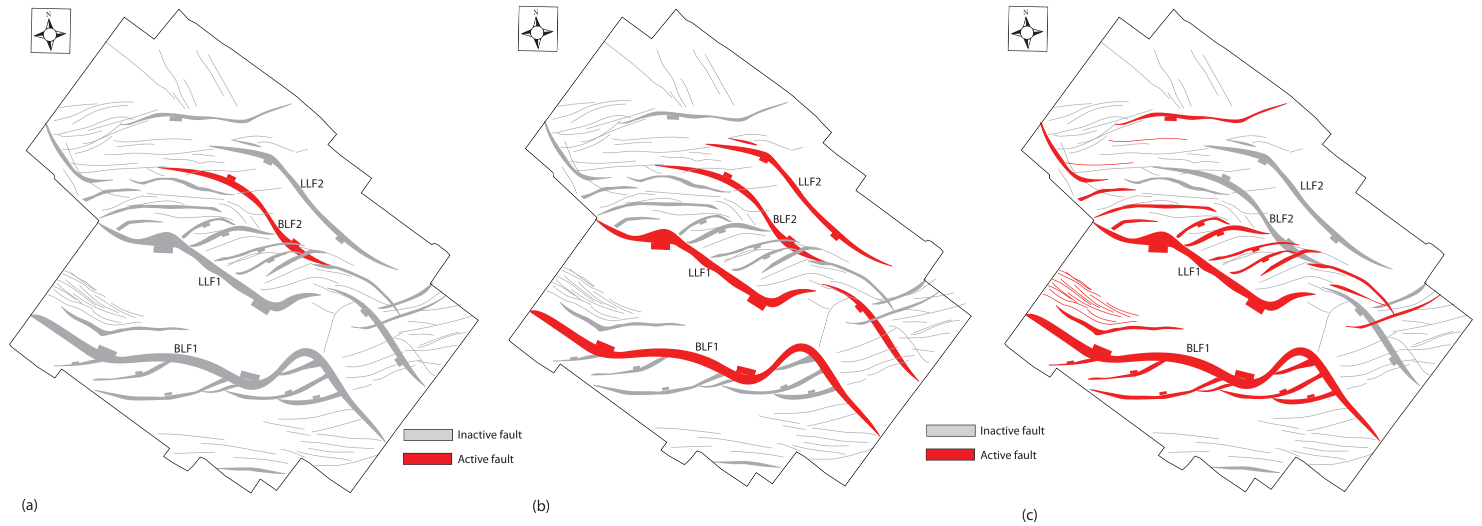

Figure 21(a-c). Timing of fault activity in Guinevere Field obtained from combination of thickness and fault maps (a) Upper Triassic fault activity (b) Lower -Middle Jurassic activity and (c) Upper Jurassic activity

Upper Triassic

The thickness map generated for the interval between the Base Haisborough and Base Lias (Fig. 18) represent the Upper Triassic thickness, it shows evidence of sediment thickening accross BLF2 which implies that it is active during this period forming an asymmetric half graben. The map displays sediment thickness variations with area towards the NE having thick sediments and a relative uniform thickness in the SW part. As observed from the thickness above BLF2 is the only active fault out of the four major graben bounding faults as indicated in Figure 21a.

Lower-Middle Jurassic

The thickness map generated for the interval between the Base Lias and Base Kimmeridge (Fig. 19) represent the Middle Jurassic thickness, it shows the two grabens (1 and 2) fully developed with considerable sediment thickness at their centres indicating that graben bounding faults (BLF1,LLF1,BLF2 and LLF2) are active during this period (Fig. 21b). This suggest that the main phase of faulting activity occurred during the Lower

Upper Juassic - Cretaceous

The Base Kimmeridge-Sea Bed thickness map (Fig. 20), which represents the Lower Cretaceous Period thickness, it shows that BLF1 and LLF1 bounding graben 1 together with the ENE set of faults are the only active faults (Fig.20 and 21c). The BLF2 and LLF2 faults bounding graben 2 have died out during this period. The E-W fault located towards the N is also active. The Upper Jurassic records a change in stress orientation.

8 4D Graben Evolution Model

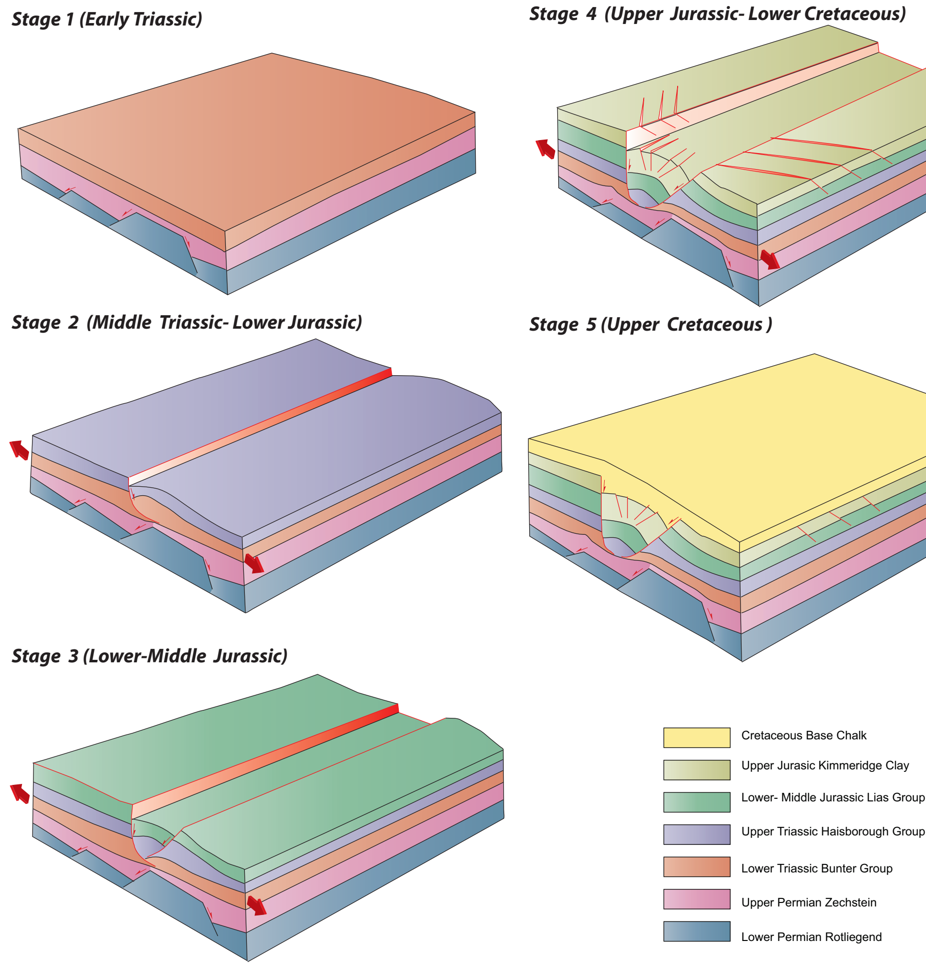

Figure 21. 4D Evolution model for complex Mesozoic Graben and Lower Triassic Separation Zones.

Stage 1 (Early Triassic)

The conformable deposition of Zechstein, Triassic evaporites and Siliclastics units took place .

Stage 2 (Middle Triassic- Lower Jurassic)

A basinward listric growth fault cut and offset the conformable Bacton Group at high angle and detached or sole out in the Upper Permian Zechstein . An asymmetric half graben is formed, this is followed by rotation of the Triassic Groups due to extension; this results in thinning of the unit against the fault as evidenced on seismic sections in Figure 8b and in Figure 15,16,and 17

Stage 3 (Lower- Middle Jurassic)

A second younger landward listric fault which was subsequently developed cut and offset the younger Jurassic sequence at low angle and detached within the inclined Upper Triassic Haisborough Group Rot Halite unit as evidenced in Figure 17. This results in the formation of graben and the Lower Triassic Separation Zone.

Stage 4 (Upper Jurassic- Lower Cretaceous)

During the Upper Jurassic- Lower Cretaceous a change in stress orientation results in the development of ENE trending faults. Seismic sections (Fig. 8b and 9b) , Kimmeridge structure maps (1Fig. 14) and thickness maps (Fig. 20) all show this.

Stage 5 (Upper Cretaceous)

Inversion and reactivation of pre-existing NW-SE faults took place during the Cretaceous. By the end of the Cretaceous, the graben bounding faults are now active, thick sediments can be observed on BLF1 and LLF1 both on seismic and thickness map (Fig. 8b and Fig. 20). The seismic lines in Fig. 8b depict the present day geometry of the Guinevere field.

9 Conclusions

The above proposed conceptual 4D model for the evolution of the complex Mesozoic grabens in Guinevere field depends largely on the presence of the two detachments layers of the Triassic Haisborough Group and the Permian Zechstein, with the two listric extensional faults (basinward listric fault and landward listric fault detaching on the Permian and Triassic detachments utilizing two different phases of extension.

The Upper Permian Zechstein detachment layer plays two important roles; the first being a surface that detaches all the basement faults via decollement from the overlying cover faults, which implies that the structures above the detachment layer are not complicated by the subsalt faults. The second role is the detaching of the cover faults or the supra salt structures, which assists in the formation of graben .

The Upper Triassic Haisborough primarily serves as second detachement layer, This layer was rotated thus becoming inclined, there by providing surface for the detachment of the landward listric fault , which leads to the formation of the complex Mesozoic graben and Lower Triassic Separation Zone described above. This therefore shows the importance of understanding dual detachment systems to explain complex Southern North Sea structures.

10 References

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