Tectonostratigraphy and the petroleum systems in the Northern sector of the North Falkland Basin, South Atlantic.

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Abstract

The North Falkland Basin represents one of the frontier areas for hydrocarbon exploration in the South Atlantic. This study presents the results of new subsurface mapping using 2D seismic data in the north of the Falkland Islands offshore area, which has delineated a series of discrete grabens northwards of the main North Falkland Basin, referred collectively to as the Northern sector of the North Falkland Basin (NNFB). Six regionally significant seismic reflectors are interpreted within this data, dividing the sedimentary fill into six tectonostratigraphic packages, including: early syn-rift; late syn-rift; transitional unit; early post-rift; middle to late post-rift; and a sag unit. Structural interpretation of the 2D seismic data has led to the definition of four north-south orientated depocentres, namely: (1) the Eastern Graben, largest of the depocentres; 20km wide by 45km long, reaching depths of 3km; (2) the Eastern Graben Splay, a smaller depocentre; 10km wide by 20km long, reaching depths of 2-2.5km; (3) the Western Graben Splay, the smallest depocentre; 5km in width and 20km long, with a basin depth of 2km and (4) the newly defined Phyllis Graben, which is 13km wide and 30km long, with a basin depth of 3km. A network of NW-SE and NE-SW trending faults controls the development of these grabens, separated by a Western, Eastern and Intra-Basin high. These grabens represent a northern continuation of the Northern Falkland Basin to the south. Hydrocarbon discoveries to the south of this study area (e.g. Sea Lion, Casper, Beverley, Zebedee, Isobel Deep, and Liz) confirm a working petroleum system adjacent to the Northern sector. This study has identified a number of

seismic anomalies, including amplitude brightening events, which potentially correspond to an extension of this petroleum system, indicating active migration pathways. The main targets, in terms of hydrocarbon interest in the northern sector, are likely to be stratigraphically trapped hydrocarbon accumulations, contained within vertically-amalgamated turbidite fan sandstone reservoirs, deposited within the early post-rift. A second, yet to be tested, syn-rift play, in which the trapping geometries are structural and the reservoirs are fluvial sandstones is also identified.

1. Introduction

The Falkland Islands offshore designated area for exploration covers approximately ~460,000 km^2 and has received relatively little attention in terms of hydrocarbon exploration. It is composed of four main sedimentary basins of Mesozoic to Cenozoic-age; namely the North Falkland, Falkland Plateau, South Falkland and Malvinas basins, which lie north, east, south and south-west of the islands respectively (Fig. 1). The most extensively explored and so far successful of these basins in terms of hydrocarbon prospectivity is the North Falkland Basin (NFB). More specifically, the Eastern Graben of the NFB, (Fig. 2) which has been the main focus of hydrocarbon exploration since the 1990s (Lohr and Underhill, 2015; MacAulay, 2015; Richards and Hillier, 2000a and b; Thomson and Underhill, 1999; Williams and Newbould, 2015). Commercial interest, in terms of hydrocarbon potential of the NFB, has grown considerably with a number of successful exploration campaigns between 2010-2015.

Initial exploration of the NFB between 1998 and 1999 focused on targeting late post-rift sandstones draped over structural highs in the central parts of the NFB (MacAulay, 2015), an exploration strategy influenced by North Sea-style tilted fault block plays (Richards et al. 1996a). Despite encountering an excellent, organic-rich, Lower Cretaceous-aged lacustrine source rock (up to 7.5% TOC) during drilling (Richards and Hillier, 2000b; Farrimond et al., 2015), this campaign did not encounter economical resources of hydrocarbons. However, the presence of oil and gas shows in several wells indicated a number of elements of a working petroleum system, including a mature source rock; reservoir potential sandstones and a competent seal. The quantity of oil expelled from the source rock into the NFB is estimated to be approximately 60 billion barrels of oil (Richards and Hillier, 2000b).

Subsequently, exploration concepts shifted to basin margin-derived early post-rift sandstones. In particular, the reservoir concepts of Richards et al. (2006) described basin-margin attached fans prograding into lacustrine waters, ranging from alluvial fan, fan delta to deep-lacustrine fan systems, forming at various palaeo-water depths (Richards et al., 2006). Seismically bright amplitude anomalies, identified on 3D seismic data were, described by Richards et al. (2006), indicated various potential sediment entry points.

The 2010-2011 exploration campaign, was successful in discovering commercial quantities of hydrocarbons in the NFB and proved the basin margin-derived reservoir concept (MacAulay, 2015; Richards et al., 2006). This campaign targeted easterly-derived turbidite fan deposits (Bunt, 2015; Williams, 2015; Dodd et al., 2019), which form a stacked, margin-fringing succession within the Lower Cretaceous packages of the early post-rift (Fig. 3), along the Eastern Flank of the North Falkland Basin's Eastern Graben (Fig. 2). The major success of the Sea Lion discovery (Francis et al., 2015; Griffiths, 2015; MacAulay, 2015; Williams, 2015) was a turning point for exploration success within the basin. Following Sea Lion , a number of analogous targets were drilled between 2010-2011 within the same play, leading to the discovery of hydrocarbons within the Casper and Beverley fans (Bunt, 2015). More recently, three wells were drilled in the NFB, leading to further discoveries in the early post-rift, such as the Zebedee and Isobel Deep Fans in 2015. These discoveries not only extended the spatial and stratigraphic extent of the petroleum system, they highlighted the further potential for future significant discoveries in the North Falkland Basin.

One area that has remained underexplored since the initial campaign in 1998 is the NNFB (Fig. 2), which is essentially an extension of the main NFB, and likely contains a succession of early post-rift lacustrine sediments, similar to those mapped in the Eastern Graben of the NFB to the south (Fig. 2). The stratigraphy of the NNFB also contains a presumably older, syn-rift succession, which is structurally complex and remains completely un-explored.

This study addresses the following key questions:

1. What is the structural configuration of the NNFB?
2. What are the main controls on the structural configuration (i.e. timing and style of faulting)?
3. How does the basin configuration and fill compare and contrast with the Eastern Graben towards the south?
4. What is the nature of the tectonostratigraphy of the grabens in this area?
5. What are the likely petroleum systems and plays in the NNFB?

2. Geological Background

The NFB, described as a failed rift system (Richards et al., 1996a and b; Richards and Fannin, 1997; Lohr and Underhill, 2015), comprises a series of depocentres following two dominant structural trends: N-S oriented faulting is predominant in the northern area; whilst significant WNW-ESE oriented faults control the Southern North Falkland Basin (Fig. 2). Initial rifting of the NFB is likely to have initiated in the late Jurassic or early Cretaceous (Richards and Fannin, 1997). This rifting phase was followed by a thermal sag phase that began in the Berriasian-Valanginian (Richards, 2002). The environment of deposition throughout this sag phase is thought to be predominantly continental and deep lacustrine until Albian-Cenomanian times, when the basin began to develop increasingly marine conditions (Richards et al., 1996a and 1996b; Richards and Fannin, 1997; Richards and Hillier, 2000a).

The main depocentre of the NFB is orientated N-S, is approximately 30 km wide and 250 km long, referred to here as the Eastern Graben (Fig. 2). A shallower depocentre is present towards the west, termed here the Western Graben, and is separated from the main Eastern Graben by an intra-graben high known as the Orca Ridge. In this Eastern Graben, the basin displays an asymmetric half-graben geometry which is downthrown to the east (Fig.3a; Dodd et al., 2019; Richards et al., 1996a and 1996b; Richards and Fannin, 1997; Richards and Hillier, 2000a; Lohr and Underhill, 2015). The footwall to main basin bounding faults are composed of a Devonian-Permian platform (Richards et al., 1996a). In addition, there are a number of subsidiary depocentres immediately east of the Eastern Graben, all of which follow a similar N-S trend (Figs. 1 and 2).

The Southern North Falkland Basin (SNFB) represents an area intersected by a series of en-echelon WNW-ESE faults, which are easily identifiable on seismic data and gravity data (Fig. 2). The WNW-ESE faults are typically offset by the main N-S faults, suggesting two significant and distinct phases of extension, potentially associated with separate phases of rifting (Bransden et al., 1999). The older, WNW-ESE faults are similar in orientation to the trend of the Palaeozoic thrust sheets developed to the NW of the islands (Richards and Fannin, 1997; Storey et al., 1999). The WNW-ESE faults were possibly formed by reactivation of the onshore structures (Richards et al., 1996; Aldiss and Edwards, 1999). Although no well data exists in this part of the basin, the timing of this reactivation and basin development is thought to be coeval with the initial development of South Africa's Outeniqua basin during the Kimmeridgian (Thomson, 1998; Broad et al., 2012; Stanca et al., 2019).

2.1 Seismic stratigraphy of the North Falkland Basin

A tectonostratigraphic model for the NFB was presented by Richards and Hillier (2000a). The eight tectonostratigraphic units identified are: pre-rift/basement; early syn-rift; late syn-rift; transitional/sag; early post-rift; middle post-rift; late post-rift; and a post uplift sag phase (Fig. 4; Richards and Hillier, 2000a). The post rift succession is further divided into a number of sub-units, including: LC2, LC3 and LC4 in the early post-rift; LC5, LC6 and LC7 in the middle post-rift; and L/UC1 and UC1 in the late post-rift, where 'LC' is Lower Cretaceous and 'UC' is Upper Cretaceous (Fig. 4). Previous seismic interpretation studies of the NFB have discussed different stratigraphic schemes (Fig. 4; Lawrence et al., 1999; Lohr and Underhill, 2015; Lorenzo and Mutter, 1988; MacAulay, 2015; Richards et al., 1996; Richards and Fannin, 1997 and Richardson and Underhill, 2002).

The pre-rift (basement) has been encountered in one well in the basin (14/09-1) which targeted an intra-basin high. At this well location (see Fig.2), the pre-rift comprises Devonian to Jurassic lithologies (Richards and Hillier, 2000a), and as a consequence of limited data, remains poorly understood.

The earliest phase of rifting initiated in the late Jurassic, and lasted until the Lower Cretaceous (Richards, 2002). During this time, an early to late syn-rift succession, comprising conglomerates, sandstones, organic-rich mudstones, and reworked tuffs, was deposited in a fluvial to lacustrine environment (Richards and Hillier, 2000a). Subsequently, the basin experienced a transitional-sag phase in which a succession of organic-rich lacustrine claystones were deposited (Richards et al., 1996a).

A succession of early post-rift sediments was deposited during the early Cretaceous (Berriasian to Aptian), resulting in a laterally and vertically extensive lacustrine mudstone and sandstone succession (Richards and Hillier, 2000a). Sediments were transported into the basin through fluvial-deltaic systems prograding from the northern-most extent of the basin, along the Eastern Graben axis, towards the south. Concomitant with this, sands were also transported into the Eastern Graben from the flanks, along feeder systems that fed a series of turbidite fans; creating a complex, heterogeneous succession of sandstones and interbedded mudstone facies (as described in Dodd et al*.,* 2019). In particular, the easterly-derived sandstones currently represent the main reservoir lithologies identified in the NFB, to date.

During the Lower Cretaceous (Aptian-Albian) the basin fill began to develop as a thick succession of middle to late post-rift sediments were deposited. Here the sediment fill is characterised by a transition from a lacustrine dominated succession to terrestrial-fluvial systems (Richards and Hillier, 2000a).

In the late post-rift (Albian to Palaeocene) the basin experienced the first significant marine transgression. The resulting sediments comprised of claystone interbedded with sandstone, deposited in a restricted, marginal marine or lagoonal environment (Richards and Hillier, 2000a). Following the late post-rift (Palaeocene) the region underwent significant uplift, during which up to 800 m of overburden is thought to have been removed from parts of the basin (Richards et al., 1996a and b). The post uplift sediments consist of a dominant succession of claystone with interbedded sandstone, deposited in a fully developed marine basin environment (Richard and Hillier, 2000a).

3. Datasets and Methodology

This study uses 1,250 km of 2D seismic reflection data (the “FALK2000” survey) collected and processed by Veritas in 2000 on behalf of Lasmo plc, located north of operated blocks PL001, PL032 and PL033 (Fig. 5). The seismic data is post stack time migrated, which displays a positive polarity and the data is zero-phased. These seismic lines have a line spacing of 2.5-5 km in an N-S orientation and 2.5-10 km in an E-W orientation. Overall, the quality of the 2D seismic data is of reasonable quality down to 3-3.5 seconds two-way-travel-time (TWTT). Beyond this, the signal to noise ratio increases significantly and the reflections become chaotic (Figs. 3, 6 and 7). In addition to the seismic reflection data, major structures and basins were identified using Bouguer gravity data (Fig. 2) from global marine data (Sandwell et al., 2014).

To date, there are no wells within the study area (Fig. 5); however, a seismic correlation has been made from the “FALK2000” 2D survey, southwards into the “Company Composite” 3D seismic survey (Figs. 2 and 8) which consists of several merged 3D seismic datasets acquired by Shell in 1997; Desire in 2004 and Rockhopper in 2007 and 2011. This profile intersects the nearest well to the study area (14/05-1A) and wells near the Sea Lion discovery (14/10-2, 14/10-3, 14/10-5 and 14/10-7). In these more southerly areas, geological understanding is more mature and the stratigraphy is better constrained. These tie-lines enabled seismic well picks to be interpreted across into the study area, providing some stratigraphic control on the interpretation.

Seismic data were interpreted using seismic and stratigraphic concepts (sensu Mitchum et al., 1977; Vail et al., 1977; Hubbard et al., 1985). TWTT surface maps were produced from the seismic interpretation, gridded at 100 m increments. Fault polygons were created through extrapolation of 2D fault segments using a standard triangulation gridding algorithm method.

4. Tectonostratigraphy

In the NNFB, six regionally significant seismic reflections were identified within the 2D seismic data (Figs. 6 and 7), defining six tectonostratigraphic units (Fig. 4). These units have been defined by extrapolation of seismic data from the main Eastern Graben of the NFB (Fig. 8). The seismic reflectors defining these units are: top basement (TB); top early syn-rift (TESR); top late syn-rift (TLSR); top transitional/sag (TS); top early post-rift (TEPR); and top late post-rift (TLPR).

4.1 Basement and syn-rift (TB, TESR and TLSR)

The deepest reflector that can be mapped on a regional scale, the top basement (TB), forms an unconformable surface that is present across the entire seismic survey (Figs. 6 and 7). In the northern sector of the NFB, top basement is less clearly imaged below 3 seconds TWTT, while further south in the main Eastern Graben, the basin deepens with the "TB" reflector found around 4 seconds TWTT (Fig. 4). It often presents as a very bright amplitude on basement highs such as the Eastern Flank, whilst in deeper parts of the seismic data, there are small (<1 km wide), discontinuous, high amplitude reflections beneath the "TB" reflector (Fig. 6). It is possible these features could represent either igneous intrusive bodies (dykes or sills) or Devono-Carboniferous metasediments, deposited prior to the basin rifting event (Fig. 6). Two dyke swarms have been identified onshore Falkland Islands (Stone et al., 2008; Richards et al., 2013), with ages of 188-178 Ma and 135-121 Ma.

The seismic reflector marking the top of the early syn-rift (TESR) is challenging to distinguish laterally. Internally, the early syn-rift often displays, high amplitude reflectors, which are divergent and mound-like in appearance (Figs. 6 and 8). In some places this unit thins onto pre-rift basement highs (Fig. 7), in other cases these high amplitude reflections are discontinuous and have a chaotic appearance (Fig. 6).

The top late syn-rift (TLSR) is marked by an undulating, high amplitude seismic reflector, which separates the underlying, slightly transparent late syn-rift package from the overlying transitional package (Fig. 6). In places, the late syn-rift onlaps onto the underlying early syn-rift unit (Fig. 7). The internal character of the late syn-rift is relatively transparent throughout (Fig. 6), with discrete, alternating, high and low amplitude packages observed (Fig. 7b).

4.2 Transitional to post-rift (T/S, TEPR and TLPR)

The top of the transitional/sag (T/S) reflector is marked by a high amplitude laterally continuous reflector, which onlaps against the basin margins of the Eastern Graben, as well as the Eastern Flank (Figs. 6 and 8). The transitional/sag interval is characterised by a relatively uniform sediment thickness, which only ever thins out onto the basement highs. Internally, it contains isolated, chaotic, high amplitude events (Fig. 6).

The top early post-rift reflector (TEPR) is a prominent, high amplitude reflector that is laterally continuous across this seismic survey and defines the top of the early post-rift unit (Fig. 7). Internally, this unit contains high amplitude, sheet-like reflectors at the base, along with clinoform-like geometries forming at the top of the package, which appear to downlap onto the sheet-like reflectors beneath (Fig. 8). These clinoforms prograde from the north towards to the south.

The top late post-rift seismic reflector (TLPR) is laterally continuous across the seismic survey (Figs. 3, 6, 7 and 8). The late post-rift unit, internally, consists of laterally continuous, seismically transparent intervals at the base, developing into alternating, high and low amplitude reflectors towards the top.

The seismic package above the TLPR represents the post sag uplift sequence, which continues to the seabed. The package is generally transparent containing sub-parallel to parallel, low amplitude reflectors. Although within the package there are a few high amplitude, laterally continuous reflectors, which represent unconformable surfaces within the succession. This can be shown by downlap terminations of divergent reflectors on to these surfaces (Fig.6).

5. Structural interpretation

A number of two-way-travel time structural maps were produced from the interpretation of the 2D seismic data in order to understand the structural evolution of the NNFB (Fig. 9). A map of top basement (Fig. 9a) shows four N-S orientated structural lows, defined from west to east as the: Western Graben Splay; Eastern Graben; Eastern Graben Splay; and the Phyllis Graben. The Western Graben Splay, Eastern Graben and Eastern Graben Splay, together, form the northern continuation of the main graben of the NFB (Fig.2). The Western High is considered to be a northward extension of the Orca Ridge to the south and therefore the Western Graben Splay is likely to be a northward extension of the Western Graben of the NFB (Fig. 2). The Western High separates the Western Graben Splay from the Eastern Graben. The Eastern Flank forms the main structural high in the eastern part of this area. This has been separated here into a spur termed the Intra-Basin High, which separates the Eastern Graben and Eastern Graben Splay (Fig. 9a).

The Eastern Flank forms the main structural high on the eastern side of the Eastern Graben and continues southwards to the Sea Lion discovery area (Fig. 2). In the southern part of the NNFB, both the Eastern Graben and Eastern Graben Splay have half-graben geometries, and deepen towards the east against the main bounding faults (Figs. 8 and 9). A series of NW-SE and NE-SW orientated faults are present across the NNFB and define the structural orientation of these grabens (Fig. 9a-9e).

The Phyllis Graben (PG), located directly to the east of the Eastern Flank (Figs. 2 and 9), is composed of a series of half-grabens that are predominantly orientated N-S. This graben also displays an asymmetrical profile, deepening towards the north-west (Figs. 6 and 9a). It is possible that the Phyllis Graben continues north of the study area, developing into a geographically larger suite of grabens, shown as N-S oriented `gravity-lows´ in Bouguer gravity data (Fig. 2). These grabens have a comparable gravity signature to that of the Eastern Graben.

By the end of the early syn-rift, all four of the main structural lows had developed (Fig. 9b). At this stage, the Eastern Graben was the deepest and spatially largest of the four depocentres. In the Eastern Graben Splay, the early syn-rift interval deepens towards the east and south against the Eastern Flank, while the Western Graben Splay deepens to the south (Fig. 9b). In contrast, the early syn-rift of the Phyllis Graben deepens north westerly. In general, the early syn-rift interval maintains a relatively consistent thickness in the study area (Fig. 7), but thickens southwards towards the Sea Lion Discovery (Fig. 8). In some areas (Fig. 7), the early syn-rift shallows up against the main bounding faults, particularly in the northern part of the Eastern Graben and Eastern Graben Splay.

The late syn-rift interval follows a similar structural pattern as the underlying early syn-rift, with increasing deepening in the centre and southern of the Eastern Graben in the NNFB. In the southern part of the NNFB, the late syn-rift onlaps the underlying early syn-rift interval against the Intra-Basin High (Fig. 7).

By the end of the transitional/sag phase, the sedimentary cover was significantly more extensive, with the overstepping of the Intra-Basin High between the Eastern Graben and Eastern Graben Splay and partially over the Western High (Fig. 9d). Structural depth increases southwards and towards the centre in the Eastern Graben, Eastern Graben Splay, whilst in the Phyllis Graben the basin depth increases northwards (Fig. 9d). Fault trends remain consistent with NW-SE and NE-SW trends observed at the top of the late syn-rift. A network of fault terraces is present at the southern extent between the Eastern Graben and Eastern Graben Splay (Fig. 9d).

By the early post-rift, the basin continued to fill with sediments, primarily within the Eastern Graben and the Eastern Graben Splay. The Western Graben Splay displays a similar amount of deepening to that exhibited during the transitional/sag phase, whilst the Phyllis Graben has experienced overall deepening. During the early post-rift units, the Phyllis Graben appears structurally deeper than the Eastern Graben, the Western Graben and the Eastern Graben Splay. Furthermore, sediments have encroached further northwards onto the Intra-Basin High (Fig. 9e). The Western Graben Splay, Eastern Graben, Eastern Graben Splay and Phyllis Graben fault trends remain consistent, with a NW-SE and NE-SW trend as seen during the transitional/sag phase.

In the late post-rift, sediment cover is preserved across the Western and Eastern Flanks, as well as the Intra-Basin High (Fig. 9f). Here, the late post-rift sediments deepen northwards in the Eastern Graben and Phyllis Graben respectively (Fig. 9f). By this phase, most of the faulting had terminated with only a few NW-SE faults remaining active.

6. Discussion

6.1 Basin development in the NNFB

This study has shown that faults that were active during the syn-rift phase remained consistently active until the early post-rift phase. The NW-SE faults observed in the NNFB may represent similar structures as those observed in the Southern North Falkland Basin, which were interpreted as reactivated thrust faults similar to those seen onshore (Richards et al., 1996; Aldiss and Edwards, 1999; McCarthy et al., 2017). The NE-SW orientated faults are likely to have formed due to the initial E-W extension associated with the opening of the South Atlantic during the late Jurassic- early Cretaceous (Richards and Fannin, 1997). These faults form a component of the fault architecture along with the NW-SE faults, defining the margins of the N-S trending depocentres, namely the Eastern Graben, Eastern Graben Splay, Western Graben and Phyllis Graben.

It is likely the initial rifting of the NNFB occurred contemporaneously with the central part of the NFB to the south. During this initial rifting, an early syn-rift phase led to the development of accommodation space within the centre of each of these grabens. This rifting continued into the late syn-rift with accommodation space increasing, particularly within the Eastern Graben (Fig. 9c). The presence of structural highs such as the Western Flank, Western High, Intra-Basin High and Eastern Flank, as well as consistent fault trends in the early and late syn-rift (Fig. 9b-9c), suggest these faults remained tectonically active throughout the syn-rift.

As rifting halted, and the NNFB entered the transitional/sag phase, the Western High and Western Flank became inactive and an overstepping succession was deposited across these highs. It is likely that during this time the amount of accommodation space developed at the edge of the Intra-Basin High started to be outpaced by sediment input, evidenced by the partial flooding and deposition of sediments over the high during this time. However, the Eastern Flank continued to remain a topographical high at the stage (Fig. 9d). The consistent presence of the NW-SE and NE-SW fault trends illustrates these faults remained active throughout the syn-rift into the transitional/sag phase. During the early post-rift, the Eastern Graben and Eastern Graben Splay formed a single connected depocentre deepening southwards and remained isolated from the Phyllis Graben by the Eastern Flank (Fig. 9e). Clinoforms observed within the early post-rift of the Eastern Graben (Fig. 8) suggest a prograding deltaic system drained into the basin from the north.

The Phyllis Graben, seems to have developed at a steady rate throughout the syn-rift and transitional/sag phase, as seen by the gradual structural deepening of the basin northwards (Fig. 9b-9d). During the early post-rift the Phyllis Graben appears to have more subsidence than the Eastern Graben (Fig. 9e), while in the late post-rift both depocentres had a consistent depth (Fig. 9f). By the late post-rift, most of this tectonic activity had ceased with only a few NW-SE faults remaining active, having either exploited crustal weaknesses derived from mid post-rift faults or though differential compaction. At this stage, the Eastern Flank was covered with sediment, as the Eastern Graben and Phyllis Graben amalgamated into a single, large depocentre (Fig. 9f).

6.2 Hydrocarbon prospectivity of the NNFB

6.2.1 Source Rock

No well data is available in the NNFB and consequently source rock intervals to the south have been used to provide analogous data. In the North Falkland Basin, the main source rock intervals are organic rich claystones within the transitional/sag and early post-rift tectonostratigraphic units (Richards and Hillier, 2000b). These claystones were deposited in an anoxic, lacustrine environment during the Berriasian to Aptian (Richards and Hillier, 2000b), and are thought to be responsible for charging the reservoirs of the Sea Lion discovery (MacAulay, 2015; Farrimond et al., 2015). The source rocks in the Early Post Rift comprise Type I and II kerogens, and generally increase in total organic carbon (TOC) from the transitional/sag unit, into the overlying early-post rift (Richards and Hillier, 2000b). Basin modelling has suggested the main phase of oil generation of the early post-rift source rock took place during the late Cretaceous between 70-100Ma (Richards and Hillier, 2000b).

Analysis of the 2010-2011 wells characterised the recovered oil samples as: “a dark, waxy, lacustrine oil with an API ranging from approximately 24-29° sourced from various oil families” (Farrimond et al., 2015). Figure 8 illustrates that the transitional and early post-rift units, which contain this main source rock interval, remain at the same depth across the main NFB and into the NNFB (between 1.7-2.3 seconds). Therefore, it is possible that hydrocarbons have been generated in this part of the basin. Continuous sub-parallel/parallel, low frequency, high amplitude reflectors in these units are likely to represent deep lacustrine organic rich claystone source rocks (Fig.8). In contrast, discontinuous reflectors are likely to represent shallow lacustrine sediments, which consist of organic lean claystone units interbedded with sandstone units.

In addition, a secondary source rock interval is likely within claystone-dominated units within a fluvial succession of the late syn-rift, deposited during the Tithonian to Berriasian (Richards and Hillier, 2000b). Rock-Eval pyrolysis studies, completed on wells 14/05-1A and 14/10-1, suggest the presence of Type II source rocks in the late syn-rift with 4.5% average TOC (Richards and Hillier, 2000b).

Basin modelling suggested an oil window between 2,800–3,500 m (Richards and Hillier, 2000b) across the NFB. In the central part of the NFB, the syn-rift package reaches depths >4,000 m, Vitrinite reflectance data suggests any source rock encountered here is likely to be within the gas window (Richards and Hillier, 2000b). However, as the syn-rift is shallower in the NNFB (c. 3,000 m) there is potential for it to be oil prone in this area.

6.2.2 Reservoirs

Fluvial sandstones have the potential to act as reservoirs within the early syn-rift (Richards and Hillier, 2000b). These sandstones have been encountered in the nearest well 14/05-1A, with several zones of net thicknesses reaching up to 40 m, with porosities ranging from 4.4–7.5% (Richards and Hillier, 2000b). Greater potential is likely in fluvial sandstones of the late syn-rift, where thicker successions have been encountered with up to 125 m of net sandstone and porosities ranging between 27.8–30.4% (Richards and Hillier, 2000b).

In the NFB, the best understood reservoir intervals are contained within the early post-rift unit, these sandstones were first identified as the primary reservoir target during the drilling campaign in 1998, and were later confirmed during the Sea Lion discovery in 2010 (Holmes et al., 2015; Williams, 2015). In the Sea Lion Fan, these reservoirs consist of well-sorted, fine- to medium grained, high-density turbidite sandstones deposited in a deep-lacustrine turbidite fan setting (Dodd et al., 2019). The fans are composed of overlapping lobes fed into the basin from the east. Reservoir quality within the sandstones in the Sea Lion Fan is generally good, with porosity and permeability values averaging 22% and 185 mD, respectively (Williams, 2015). On the 2D seismic data, similar geometries comparable to that of the Sea Lion complex are observed (Fig. 8). The Northern Lead forms a discrete, 5-7 km long, high amplitude seismic event (Fig. 8), which was deposited near to the base of the early post-rift unit. In both examples of the Sea Lion complex and Northern Lead seismic reflectors are significantly stronger than the surrounding sediments and display a "mound" like topography, within an otherwise flat lying package of reflectors, suggesting depositional relief. Laterally, both display a reduction in seismic amplitudes towards the edge of each feature and are found at the base of southerly prograding clinofroms representing delta foresets. In addition, a series of high amplitude, sheet-like seismic reflectors can also be seen in the early post-rift, which may represent hydrocarbon-filled lacustrine turbidite sandstones (Fig.7).

6.2.3 Traps

The first phase of exploration drilling in 1998 focused on targeting structural, four-way dip closures, such as drilled by well 14/09-1, which drilled on the crest of a large, titled fault block. One of the main reasons for failure was the ineffective top seal (Richards and Hillier, 2000b). In the NNFB there are a number of potential two-way and three-way dip closures identified in the hanging walls of faults in the early and late syn-rift intervals (Fig. 9b and 9c), which are yet to be tested.

In the early post-rift, there is potential for stratigraphic traps containing deltaic-top and delta-front sandstones. These sediments are likely to be part of prograding deltaic systems, which can be observed as clinoform geometries in the seismic data (Fig. 8). Furthermore, the more distal delta deposits, which are likely to be more mud-prone, provide lateral seal potential these trapping geometries.

To date the most successful trapping geometries in the North Falkland Basin are complex, combined structural and stratigraphic traps, particularly within the early post-rift (e.g., Sea Lion discovery; MacAulay, 2015; Dodd et al., 2019). Firstly, the stratigraphic component is provided by deep lacustrine turbidite fans that display abrupt, lateral pinchouts and up-dip sealing through the detachment of feeder systems facilitated through slope bypass (Dodd et al., 2019). Secondly, the structural component is provided through the draping of turbidite sands along basin margin geometries and over the inversion-related high in the centre of the Eastern Graben (Fig. 3). Finally, in places basin-margin faults aid up-dip sealing through the offsetting of turbidite fan feeder channels from the depositional lobes, providing an element of fault closure to some of these traps.

6.2.4 Seal

The regional seal across the NFB is formed by a thick mudstone succession within the early post-rift (Richards and Hillier, 2000b). The early post-rift unit is laterally extensive across the grabens of the NNFB according to the correlated seismic package (Fig. 9d), therefore likely forming a regionally effective seal. The seal will be most effective in the centre of the basin depocentres where the mudstone accumulations are likely to be thicker (Richards and Hillier, 2000b). In the NNFB there is also potential for sealing mudstones within the middle post-rift and late post-rift units (Richards and Hillier, 2000b).

6.2.5 Seismic evidence for an active petroleum system

Evidence for an active hydrocarbon system in the NFB is proven by the by the discoveries to the south. It is inferred in the NNFB from seismic anomalies present in the seismic data. In the NNFB, the early post-rift unit is intersected by major, deep-seated normal faults that penetrate through to the late post-rift, typically at the basin margins (Fig. 7). Amplitude anomalies with a negative impedance contrast, or `soft-kicks', are common, some of which can be interpreted as bright-spots (Fig. 10a). The bright spots in the Eastern Graben of the NNFB appear to occur within the middle post-rift unit, brightening near faults (Fig. 10a), which may have acted as fluid-conduits or traps for hydrocarbon migration (Fig. 10a). In addition, gas chimney features are observed cross-cutting seismic reflections (Fig. 10b). Paleo-pockmarks visible in the seismic (Fig. 10b) could indicate thermogenic or biogenic gas associated with the deeper source rock intervals (Cartwright and Santamarina, 2015). Stratigraphic packages within the early post-rift show brightening along reflections (Fig. 10c), which may indicate fluid filled sandstone packages within a turbidite fan succession, similar to those of the Sea Lion Fan (Dodd et al., 2019).

6.2.6 Summary of Petroleum System

The conceptual model for the petroleum system of the NNFB is summarised in Figure 11. In this area, the best reservoirs are likely to be within early post-rift structural-stratigraphic traps, with sand-rich turbidite fans, and the fluvial sandstones of the syn-rift in structural traps and in. The most organic rich sediments are likely to be found in the centre of the graben, in the transitional/sag unit, whilst a secondary organic rich interval maybe present along the hanging wall margins which generally represent the deepest section of the grabens during the late syn-rift unit. Moreover, both source rock intervals in the syn-rift and transitional/sag unit are likely to be mature in the NNFB as they are situated within the estimated oil window (2,250-3,000m). Finally, hydrocarbon migration potential along major faults, through and above the source/seal interval, into the overlying, thick deltaic front sandstones.

7. Conclusions

1. This study has defined the structural configuration of the Northern sector of the North Falkland Basin. The NNFB consists of two main depocentres: (a) a Western Graben and a continuation of the Eastern Graben of the NFB; and (b) a newly defined depocentre, the Phyllis Graben.
2. A series of NW-SE and NE-SW trending faults control the development of the grabens throughout the syn-rift until the late post-rift when tectonic activity ceased and sedimentation covered the entire NNFB.
3. The stratigraphy of the NNFB is separated into six tectonostratigraphic units, defined in seismic data as: early syn-rift; late syn-rift; transitional/sag; middle post-rift; late post-rift and overlying sag unit.

4. Detailed mapping has identified two hydrocarbon plays for the NNFB: i) a fluvial, syn-rift structural leads, in either 2 or 3-way dip hanging wall closures against faults; ii) an early post-rift, combined structural-stratigraphic play, which may relate to turbidite fan sandstones sourced from the north or east, analogous to well documented reservoirs found in the Sea Lion Main Complex.
5. The main source rock for the NNFB is potentially organic rich lacustrine deposits within the transitional/sag unit located in the Western Graben Splay, Eastern Graben, Eastern Graben Splay and Phyllis Graben.

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Figure Captions (all figures should be in colour for print)

Figure 1. Geological map of the offshore areas around the Falkland Islands modified after Richards et al., (1996). Red blocks show extent of the 2019 hydrocarbon exploration licences. Detailed fault interpretation of the North Falkland Basin (NFB) based on Lohr and Underhill (2015). The NFB consists of several subsidiary depocentres illustrated by the N-S orientated Mesozoic-Cenozoic basins. Inset image shows the location of the Falkland Islands with respect to South America.

Figure 2. The structural framework underlain by Bouguer gravity data of the North Falkland Basin. The Northern sector of the North Falkland Basin (NNFB) study area is illustrated with a dashed box. Grabens include: WGS - Western Graben Splay; WH - Western High; EG - Eastern Graben; EGS - Eastern Graben Splay; IBH - Intra-Basin High; PG - Phyllis Graben. The Bouguer gravity anomay map with wavelengths <100 km modified from McCarthy et al., 2017, with data from Sandwell et al., (2014). Onshore faults are taken from Aldiss and Edwards, 1999 and offshore fault interpretation modified from Lohr and Underhill, (2015). The white line are seismic sections which are illustrated across the NNFB (see Figs. 6 and 7) and the wider NFB (see Fig.4 and 8).

Figure 3. (a) E-W orientated crossline from the Company merged 3D seismic dataset, across the central part of the NFB, showing a typical cross-sectional view of the Western Graben, Orca High, Eastern Graben and Eastern Flank. The asymmetrical profile of the NFB in the

Eastern Graben deepens towards the main bounding fault. Seismic character is poor below 3.5 seconds TWT. (b) A geoseismic section showing the six reflectors interpreted in this study that define the main tectonostratigraphic units. The main bounding fault of the Western Graben, acts as a low angle detachment for antithetic faults in this part of the basin. Faults have been inferred at depth with a red dashed line and main bounding faults are labelled with fault arrows to illustrate tectonic movement. This interpretation has been adapted from Dodd et al., (2019).

Figure 4. Geological summary chart for the North Falkland Basin from Devonian to recent times. A comparison is made between seismic horizons of this study, with nomenclature from Richards and Hillier (2000a), along with lithology and environment interpretations from MacAulay (2015).

Figure 5. Orientations of 2D seismic data interpreted during this study, along with 3D seismic data used to correlate the tectonostratigraphic packages. The location of possible hydrocarbon indicators is also shown.

Figure 6. (a) E-W orientated 2D seismic line FALK 2000-020 across the northern sector of the NFB, showing a typical cross-sectional view in this study area of the northern most of the Eastern Graben, Eastern Flank and the Phyllis Graben. Seismic character is often lost beyond 3 - 3.5 seconds TWT. (b) A geoseismic section of FALK 2000-020 showing the six reflectors interpreted in this study that define the main tectonostratigraphic units. Here the Eastern Graben forms a symmetrical graben with a series of tilted rotational fault blocks in the syn-rift covered by a blanket of transitional to post-rift sediment. The Phyllis Graben displays an asymmetrical profile with sediment deepening to west against a bounding fault, with a series of synthetic faults developed.

Figure 7. (a) E-W orientated 2D seismic line FALK 2000-013 across the southern part of this NNFB study area showing the cross-sectional view of the Eastern Graben, Eastern Graben Splay, Eastern Flank of and the Phyllis Graben. Seismic amplitude character is shown down

until 3 seconds TWT. (b) A geoseismic section of FALK 2000-013 showing the six reflectors interpreted in this study that define the main tectonostratigraphic units. The Eastern Graben displays a symmetrical graben profile, whilst the Eastern Graben splay displays an asymmetrical geometry, deepening to the east against a bounding fault, which is separated from the Eastern Flank by a basement terrace. To the east, the syn-rift in the Eastern Graben Splay shallows and onlaps the Intra-Basin High. The Phyllis Graben dispays an asymmetry deepening to the west against the boundary fault, which forms the eastern edge of the Eastern Flank. There are some discrete, high amplitude features in the late syn-rift, which could represent potential stratigraphic traps for hydrocarbons.

Figure 8. A geoseismic section of N-S composite line using the 2D seismic from this study and the 3D company merged 3D seismic volume along strike of the Eastern Graben of the North Falkland Basin. This line shows the six reflectors that define the main tectonostratigraphic units. In addition, high amplitude packages compare the Sea Lion discovery with the geometries observed in the Northern Lead, both within the Early Post-Rift interval. It shows a general deepening of syn-rift sediment towards to the south directly beneath Sea Lion, whilst the transitional and post-rift sediment seems to be a consistent depth across the basin. In the early post-rift, the most prospective interval, the Northern Lead, represents high amplitude package directly beneath southerly prograding clinoforms, which is similar to that of Sea Lion.

Figure 9. A series of two-way-travel time (milliseconds) structural interpretation maps showing different tectonostratigraphic reflectors at various stages of basin evolution. Note the black polygons indicate the fault trends, whilst the black dashed lines represent sub-cropping of the unit. Areas of white demonstrate no sediment deposition at this time. (a) Top Basement (b) Top Early Syn-Rift (c) Top Late Syn-Rift (d) Transitional/Sag Phase (e) Top Early Post-Rift and (d) Top Late Post-Rift

Figure 10. Seismic anomalies found on the 2D FALK 2000 seismic dataset in the study area. (a) Bright spot amplitudes and potential fault trap (b) Gas chimneys escaping towards the surface, with visible paleo-pockmarks (c) Bright discontinuous amplitude anomalies that could represent hydrocarbon filled stratigraphic traps.

Figure 11. Schematic cross-section showing the proposed petroleum systems in the NNFB. The main source rock is located in organic-rich lacustrine deposits found within the central depocentre of each graben. There is a risk of hydrocarbon leakage along major basement bounding faults within the post-rift section. The Phyllis Graben represents a potentially new area for exploration, with analogous geometries, scale and sedimentary fill to the Eastern Graben. With additional seismic acquisition, this area could represent significant future exploration in the North Falkland Basin.

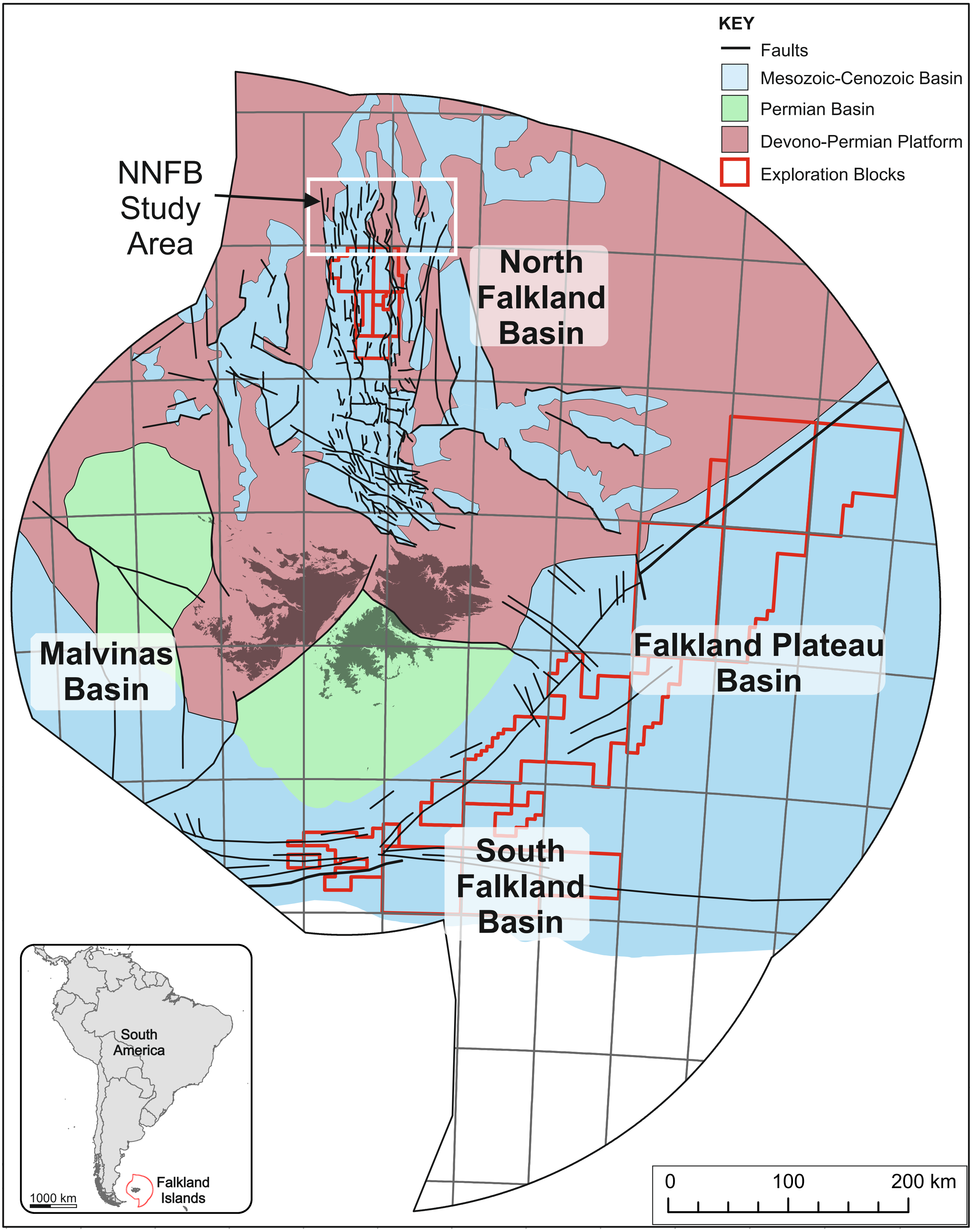

KEY
Faults
Mesozoic-Cenozoic Basin
Permian Basin
Devono-Permian Platform
Exploration Blocks
NNFB
Study
Area
North
Falkland
Basin
Malvinas
Basin
Falkland Plateau
Basin
South
Falkland
Basin
South
America
1000 km
Falkland
Islands
0
100
200 km

Figure. 1

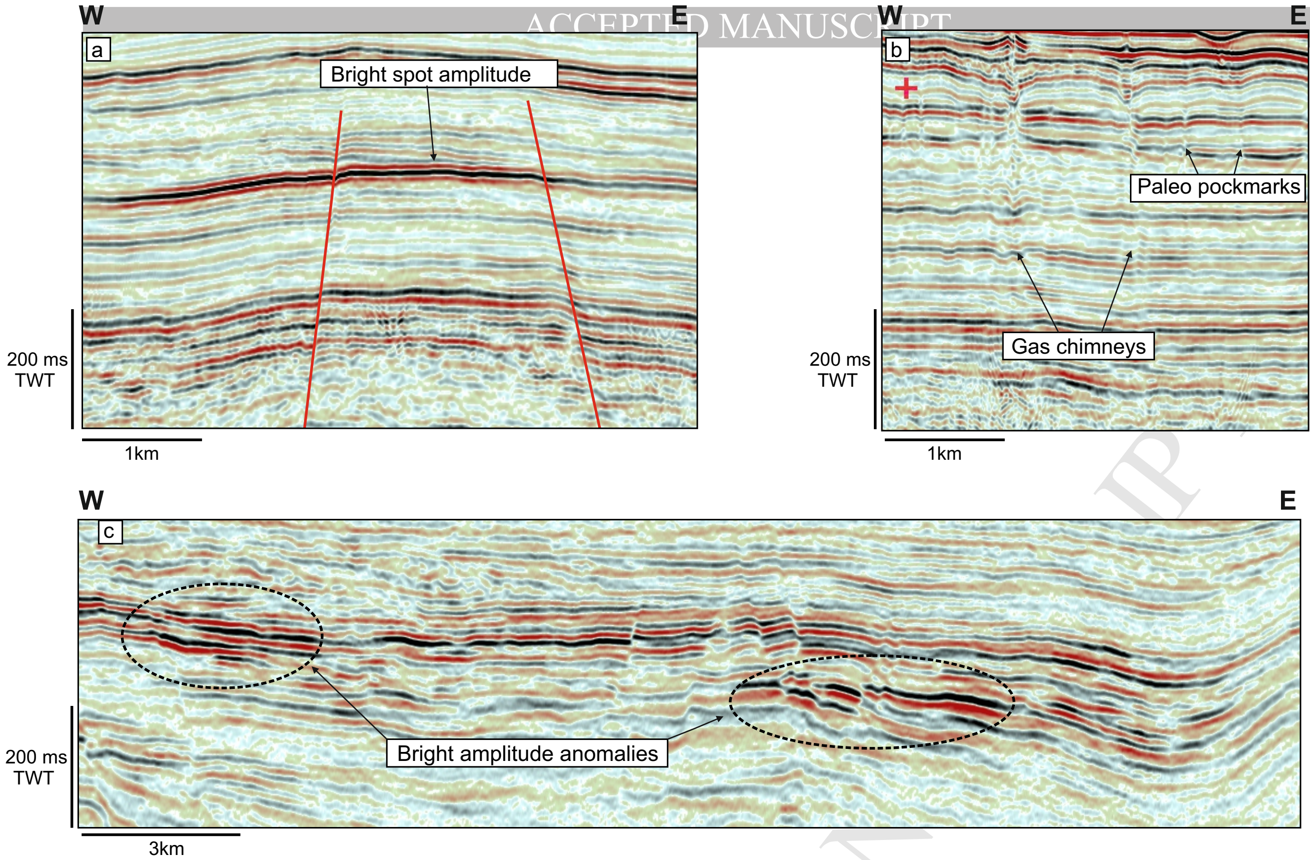
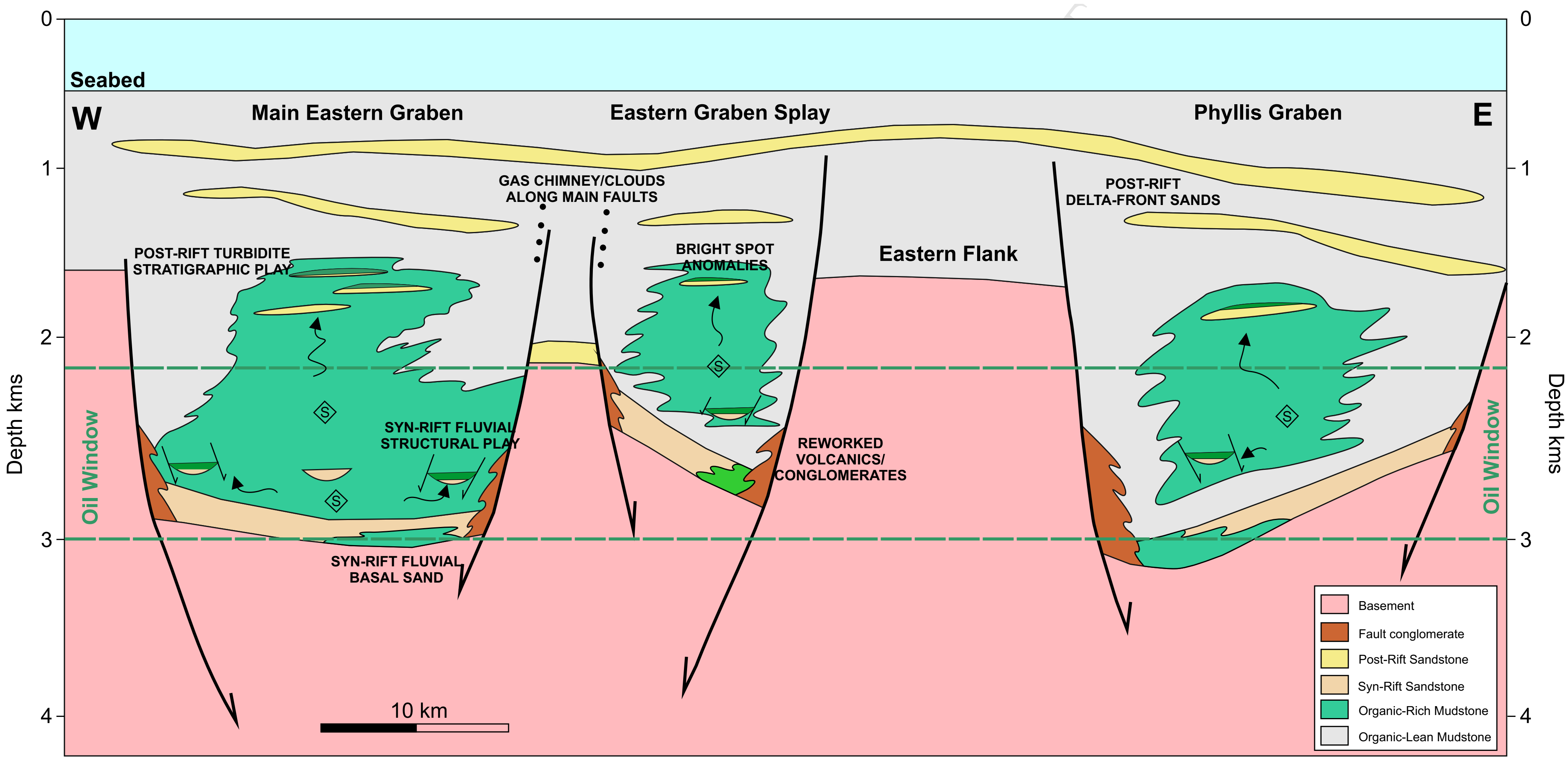

W
E
a
Bright spot amplitude
200 ms
TWT
1km
W
E
b
Paleo pockmarks
Gas chimneys
200 ms
TWT
1km
W
E
c
Bright amplitude anomalies
200 ms
TWT
3km

Figure. 10



0
1
2
3
4
Depth kms
Seabed
W
Main Eastern Graben
Eastern Graben Splay
Phyllis Graben
E
GAS CHIMNEY/CLOUDS
ALONG MAIN FAULTS
POST-RIFT
DELTA-FRONT SANDS
POST-RIFT TURBIDITE
STRATIGRAPHIC PLAY
BRIGHT SPOT
ANOMALIES
Eastern Flank
SYN-RIFT FLUVIAL
STRUCTURAL PLAY
REWORKED
VOLCANICS/
CONGLOMERATES
SYN-RIFT FLUVIAL
BASAL SAND
Oil Window
Oil Window
S
10 km
Basement
Fault conglomerate
Post-Rift Sandstone
Syn-Rift Sandstone
Organic-Rich Mudstone
Organic-Lean Mudstone

Figure. 11

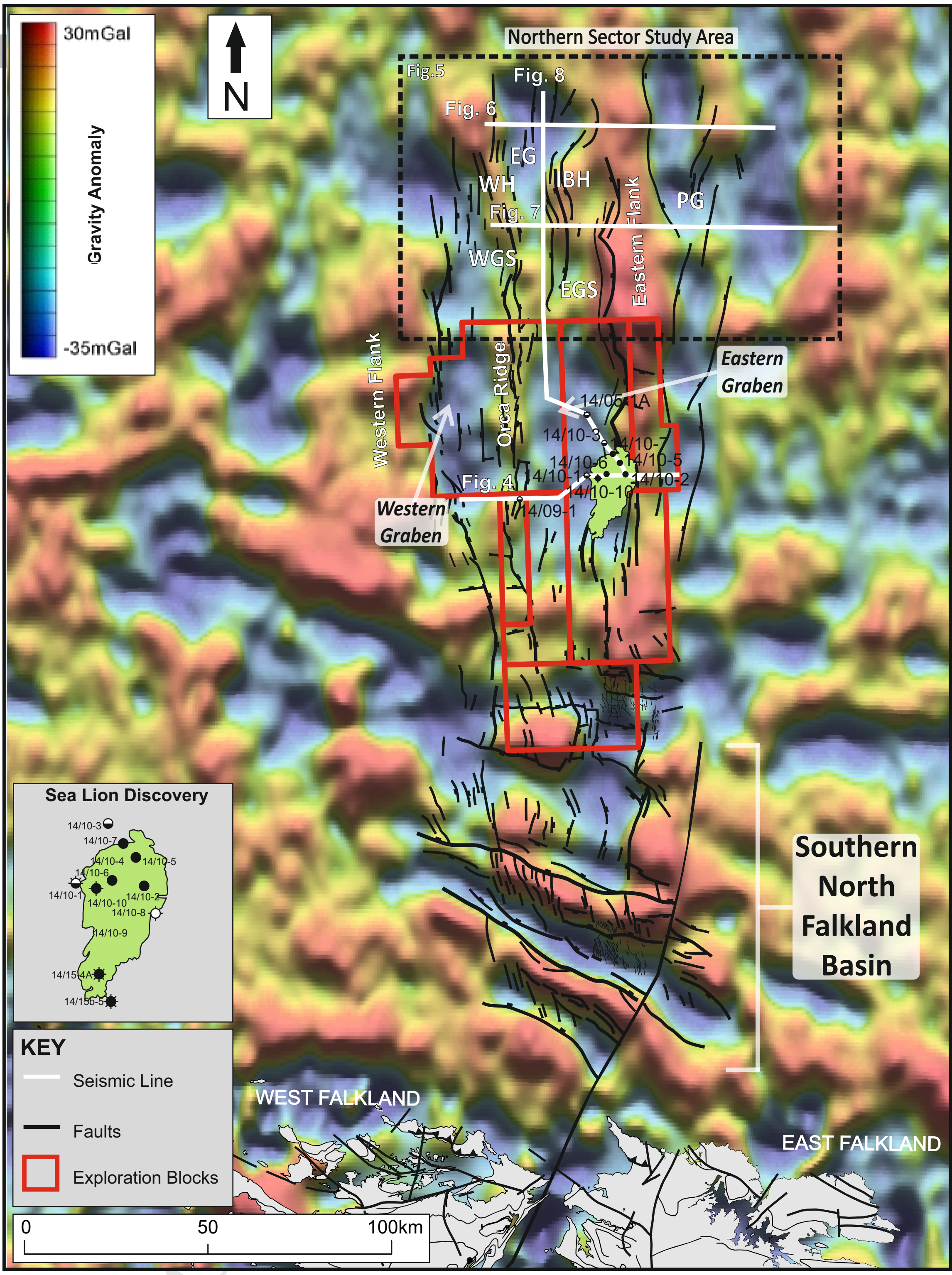
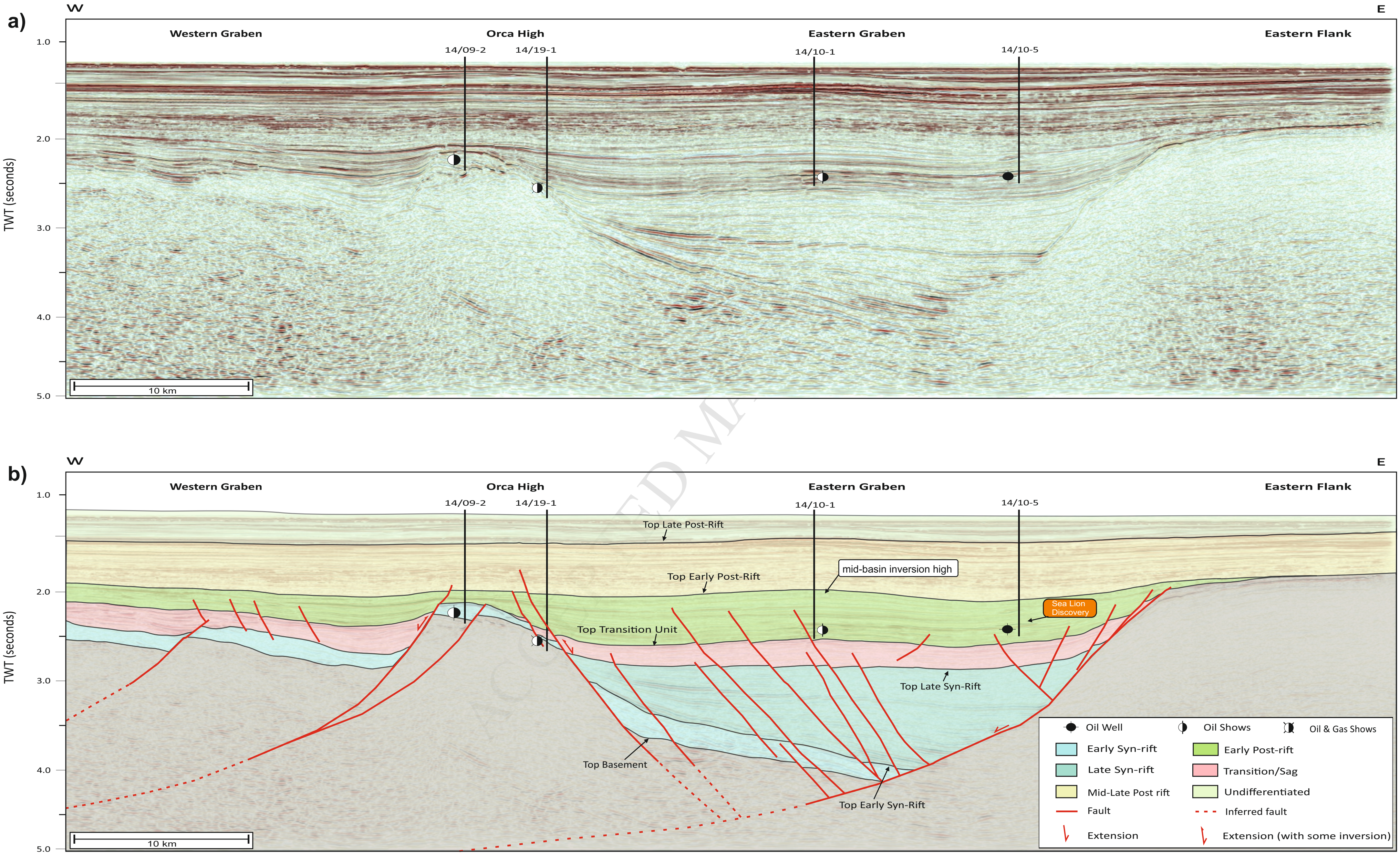

30mGal
Gravity Anomaly
-35mGal
N
Northern Sector Study Area
Fig.5
Fig. 8
Fig. 6
EG
WH
IBH
PG
Fig. 7
Eastern Flank
WGS
EGS
Western Flank
Orca Ridge
Eastern Graben
14/05-1A
14/10-3
14/10-7
14/10-6
14/10-5
14/10-1
14/10-2
14/10-10
Fig. 4
14/09-1
Western Graben
Sea Lion Discovery
14/10-3
14/10-7
14/10-4
14/10-5
14/10-6
14/10-1
14/10-10
14/10-2
14/10-8
14/10-9
14/15-4A
14/15-5
Southern North Falkland Basin
KEY
Seismic Line
Faults
Exploration Blocks
WEST FALKLAND
EAST FALKLAND
0
50
100km

Figure. 2



a)
W
E
Western Graben
Orca High
Eastern Graben
Eastern Flank
14/09-2
14/19-1
14/10-1
14/10-5
TWT (seconds)
1.0
2.0
3.0
4.0
5.0
10 km
b)
Top Late Post-Rift
Top Early Post-Rift
mid-basin inversion high
Sea Lion Discovery
Top Transition Unit
Top Late Syn-Rift
Top Basement
Top Early Syn-Rift
Oil Well
Oil Shows
Oil & Gas Shows
Early Syn-rift
Early Post-rift
Late Syn-rift
Transition/Sag
Mid-Late Post rift
Undifferentiated
Fault
Inferred fault
Extension
Extension (with some inversion)

Figure. 3

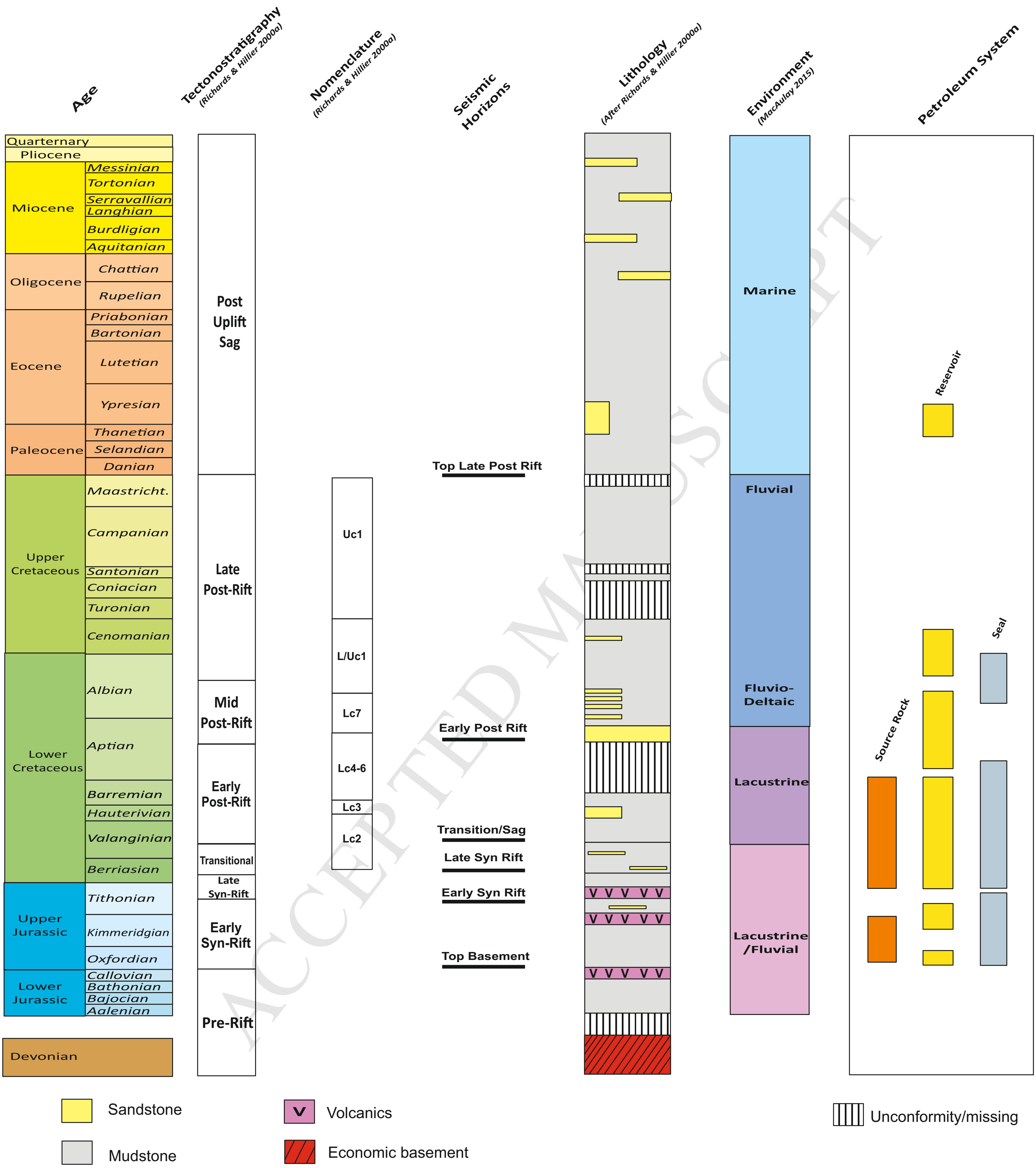

Age
Tectonostratigraphy (Richards & Hillier 2000a)
Nomenclature (Richards & Hillier 2000a)
Seismic Horizons
Lithology (After Richards & Hillier 2000a)
Environment (MacAulay 2015)
Petroleum System
Quarternary
Pliocene
Miocene
Messinian
Tortonian
Serravallian
Langhian
Burdligian
Aquitanian
Oligocene
Chattian
Rupelian
Eocene
Priabonian
Bartonian
Lutetian
Ypresian
Paleocene
Thanetian
Selandian
Danian
Upper Cretaceous
Maastricht.
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Lower Cretaceous
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Upper Jurassic
Tithonian
Kimmeridgian
Oxfordian
Lower Jurassic
Callovian
Bathonian
Bajocian
Aalenian
Devonian
Post Uplift Sag
Late Post-Rift
Mid Post-Rift
Early Post-Rift
Transitional
Late Syn-Rift
Early Syn-Rift
Pre-Rift
Uc1
L/Uc1
Lc7
Lc4-6
Lc3
Lc2
Top Late Post Rift
Early Post Rift
Transition/Sag
Late Syn Rift
Early Syn Rift
Top Basement
Marine
Fluvial
Fluvio-Deltaic
Lacustrine
Lacustrine /Fluvial
Reservoir
Seal
Source Rock
Sandstone
Mudstone
Volcanics
Economic basement
Unconformity/missing

Figure. 4

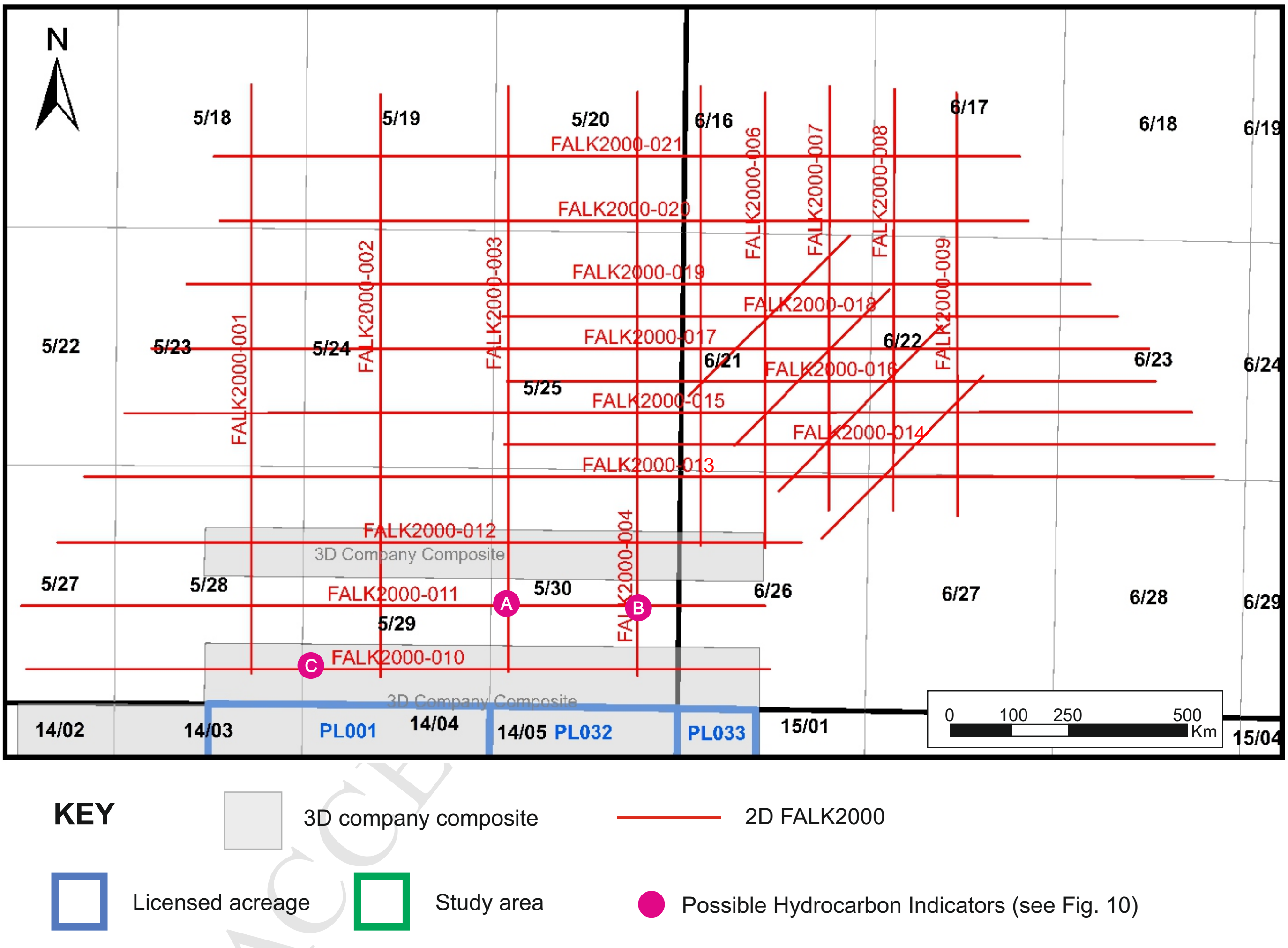
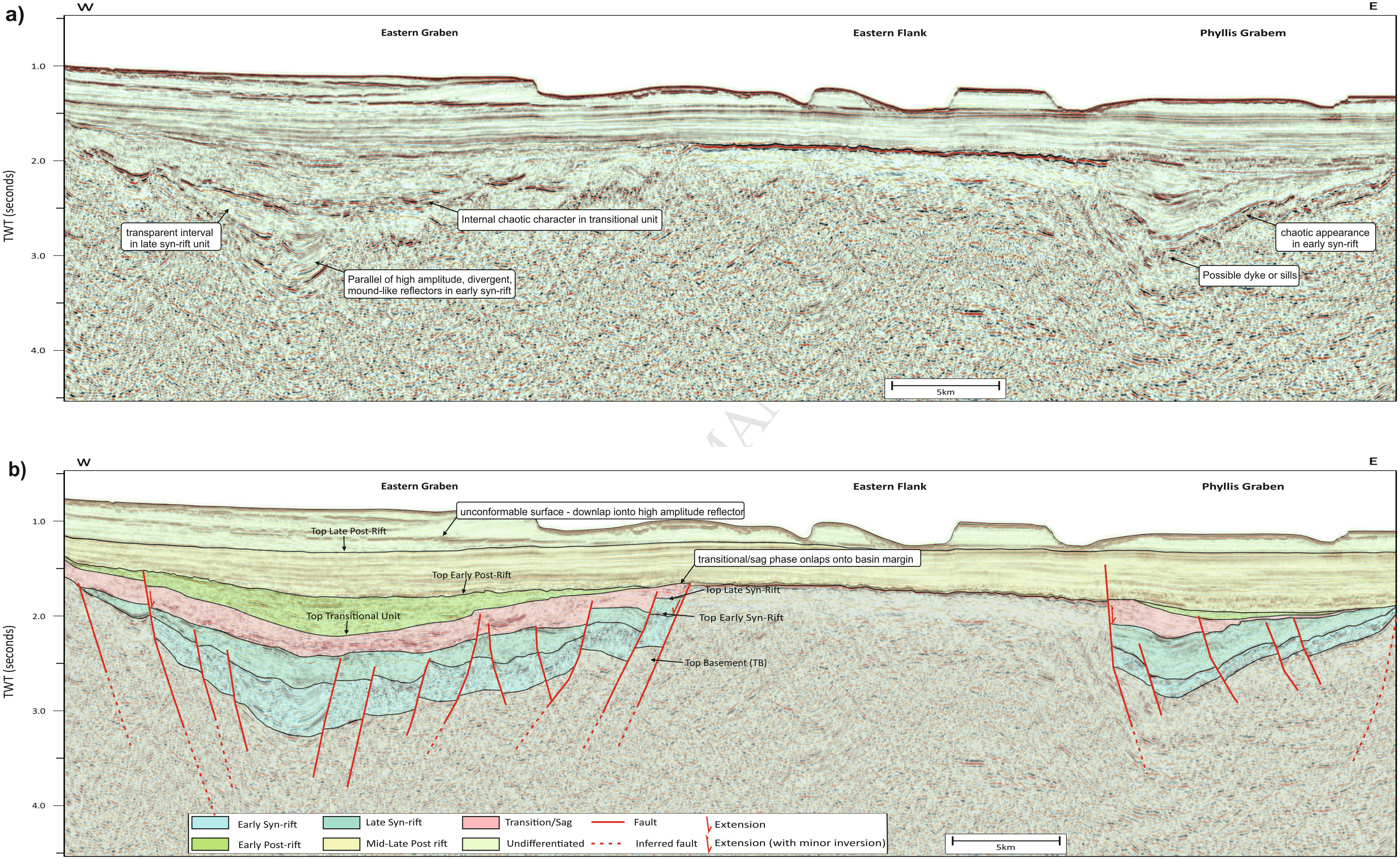

N
5/18
5/19
5/20
6/16
6/17
6/18
6/19
FALK2000-021
FALK2000-020
FALK2000-019
FALK2000-018
FALK2000-017
FALK2000-016
FALK2000-015
FALK2000-014
FALK2000-013
FALK2000-012
FALK2000-011
FALK2000-010
FALK2000-001
FALK2000-002
FALK2000-003
FALK2000-004
FALK2000-006
FALK2000-007
FALK2000-008
FALK2000-009
5/22
5/23
5/24
5/25
6/21
6/22
6/23
6/24
3D Company Composite
5/27
5/28
5/29
5/30
6/26
6/27
6/28
6/29
A
B
C
14/02
14/03
PL001
14/04
14/05
PL032
PL033
15/01
15/04
0 100 250 500 Km
KEY
3D company composite
2D FALK2000
Licensed acreage
Study area
Possible Hydrocarbon Indicators (see Fig. 10)

Figure. 5



a)
W
E
Eastern Graben
Eastern Flank
Phyllis Grabem
TWT (seconds)
1.0
2.0
3.0
4.0
transparent interval in late syn-rift unit
Internal chaotic character in transitional unit
Parallel of high amplitude, divergent, mound-like reflectors in early syn-rift
chaotic appearance in early syn-rift
Possible dyke or sills
5km
b)
W
E
Eastern Graben
Eastern Flank
Phyllis Graben
unconformable surface - downlap ionto high amplitude reflector
Top Late Post-Rift
transitional/sag phase onlaps onto basin margin
Top Early Post-Rift
Top Late Syn-Rift
Top Transitional Unit
Top Early Syn-Rift
Top Basement (TB)
Early Syn-rift
Late Syn-rift
Transition/Sag
Fault
Extension
Early Post-rift
Mid-Late Post rift
Undifferentiated
Inferred fault
Extension (with minor inversion)
5km

Figure. 6

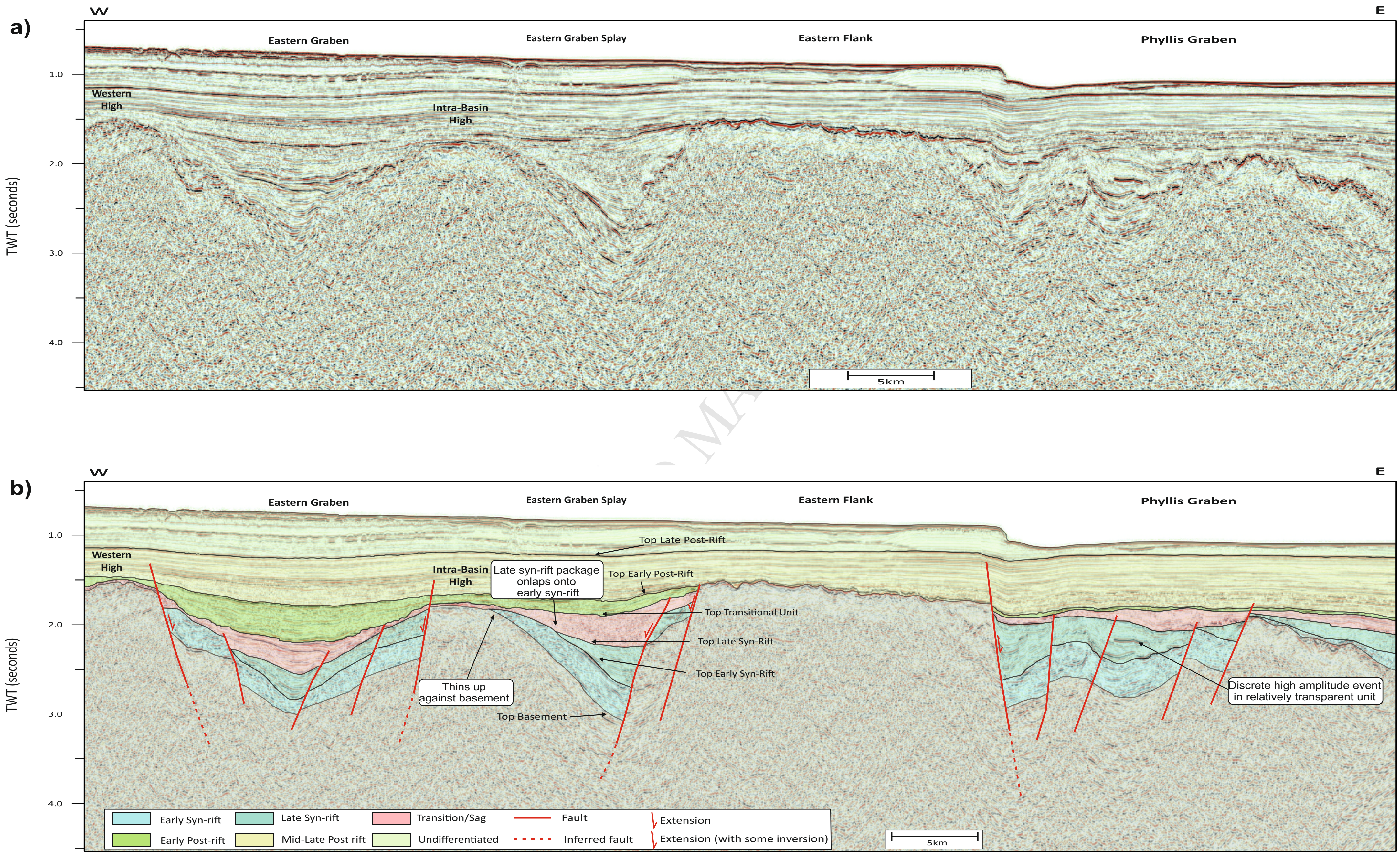
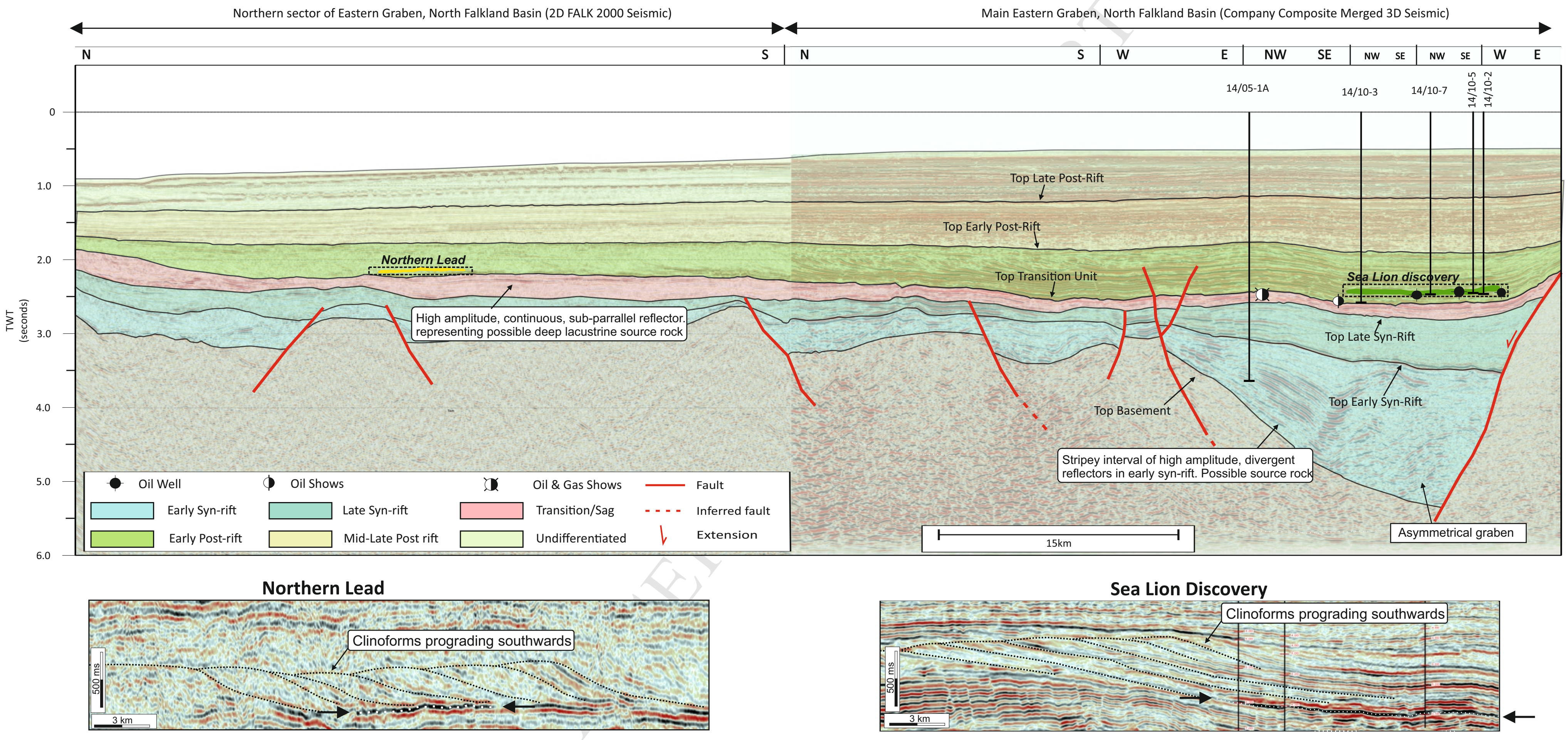
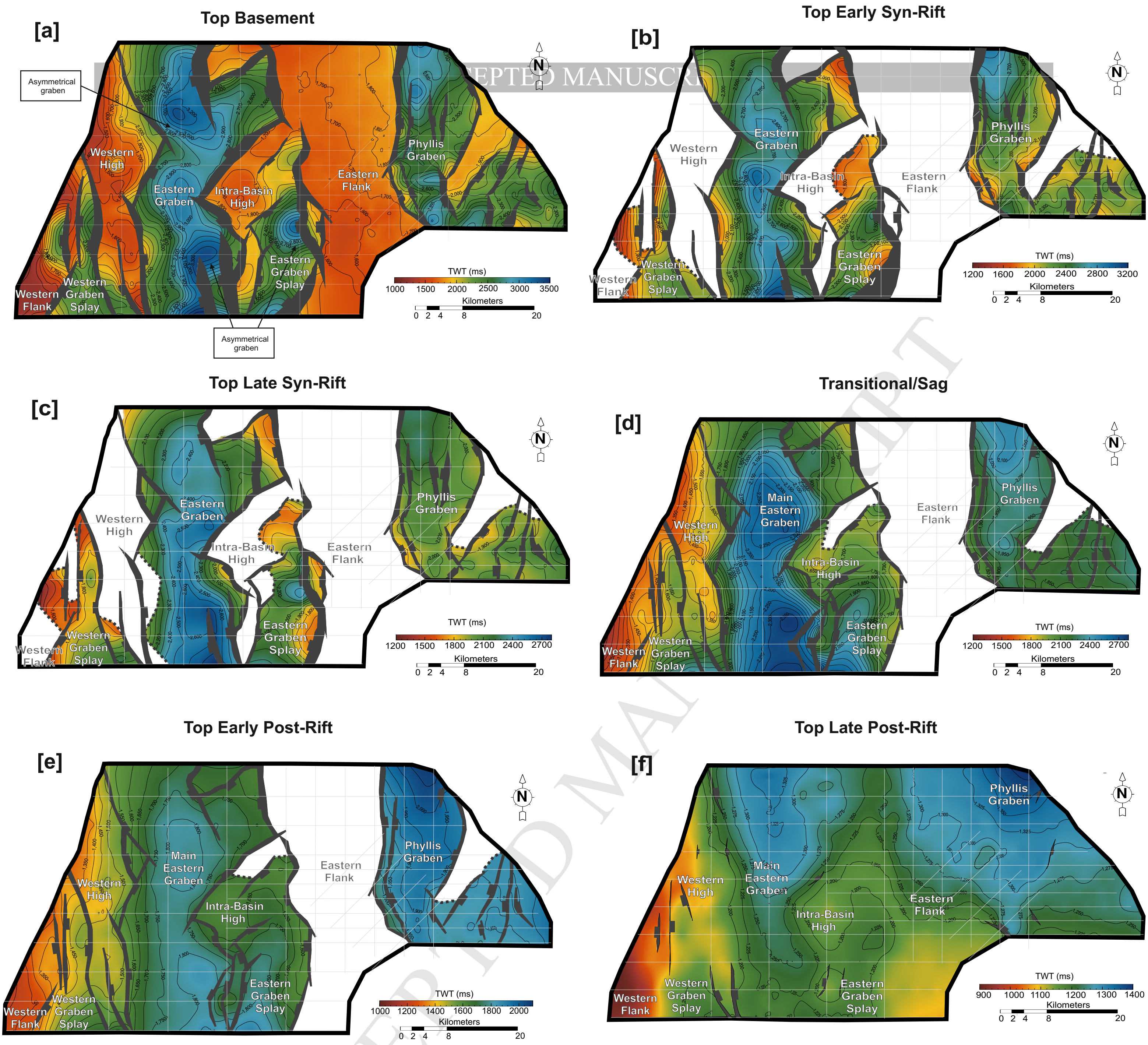

a)
W
E
Eastern Graben
Eastern Graben Splay
Eastern Flank
Phyllis Graben
Western High
Intra-Basin High
TWT (seconds)
1.0
2.0
3.0
4.0
5km
b)
W
E
Eastern Graben
Eastern Graben Splay
Eastern Flank
Phyllis Graben
Western High
Intra-Basin High
Late syn-rift package onlaps onto early syn-rift
Top Late Post-Rift
Top Early Post-Rift
Top Transitional Unit
Top Late Syn-Rift
Top Early Syn-Rift
Thins up against basement
Top Basement
Discrete high amplitude event in relatively transparent unit
TWT (seconds)
1.0
2.0
3.0
4.0
Early Syn-rift
Late Syn-rift
Transition/Sag
Fault
Extension
Early Post-rift
Mid-Late Post rift
Undifferentiated
Inferred fault
Extension (with some inversion)
5km

Figure. 7



Northern sector of Eastern Graben, North Falkland Basin (2D FALK 2000 Seismic)
Main Eastern Graben, North Falkland Basin (Company Composite Merged 3D Seismic)
N
S
N
S
W
E
NW
SE
NW
SE
NW
SE
W
E
14/05-1A
14/10-3
14/10-7
14/10-5
14/10-2
TWT (seconds)
0
1.0
2.0
3.0
4.0
5.0
6.0
Top Late Post-Rift
Top Early Post-Rift
Top Transition Unit
Northern Lead
Sea Lion discovery
High amplitude, continuous, sub-parrallel reflector representing possible deep lacustrine source rock
Top Late Syn-Rift
Top Early Syn-Rift
Top Basement
Stripey interval of high amplitude, divergent reflectors in early syn-rift. Possible source rock
Asymmetrical graben
Oil Well
Oil Shows
Oil & Gas Shows
Fault
Early Syn-rift
Late Syn-rift
Transition/Sag
Inferred fault
Early Post-rift
Mid-Late Post rift
Undifferentiated
Extension
15km
Northern Lead
Clinoforms prograding southwards
500 ms
3 km
Sea Lion Discovery
Clinoforms prograding southwards
500 ms
3 km

Figure. 8



[a]
Top Basement
Asymmetrical graben
Western High
Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Eastern Graben Splay
Western Flank
Western Graben Splay
Asymmetrical graben
TWT (ms)
1000 1500 2000 2500 3000 3500
Kilometers
0 2 4 8 20
[b]
Top Early Syn-Rift
Western High
Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Western Flank
Western Graben Splay
Eastern Graben Splay
TWT (ms)
1200 1600 2000 2400 2800 3200
Kilometers
0 2 4 8 20
[c]
Top Late Syn-Rift
Western High
Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Western Flank
Western Graben Splay
Eastern Graben Splay
TWT (ms)
1200 1500 1800 2100 2400 2700
Kilometers
0 2 4 8 20
[d]
Transitional/Sag
Western High
Main Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Western Flank
Western Graben Splay
Eastern Graben Splay
TWT (ms)
1200 1500 1800 2100 2400 2700
Kilometers
0 2 4 8 20
[e]
Top Early Post-Rift
Western High
Main Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Western Flank
Western Graben Splay
Eastern Graben Splay
TWT (ms)
1000 1200 1400 1600 1800 2000
Kilometers
0 2 4 8 20
[f]
Top Late Post-Rift
Western High
Main Eastern Graben
Intra-Basin High
Eastern Flank
Phyllis Graben
Western Flank
Western Graben Splay
Eastern Graben Splay
TWT (ms)
900 1000 1100 1200 1300 1400
Kilometers
0 2 4 8 20

Figure. 9

Highlights

- Four main depocentres in the NNFB are identified in 2D seismic data
- NW-SE and NE-SW trending faults controlled syn-rift graben development
- Six tectonostratigraphic units are identified and described across the NNFB
- Identification of hydrocarbon plays within early post-rift and syn-rift
- The NNFB forms an extension of the proven NFB petroleum system