Tectono-stratigraphic Evolution of the West Orkney Basin: Implications for Hydrocarbon Exploration

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Submitted in partial fulfilment of the requirements for the degree of Ph.D

Cardiff University

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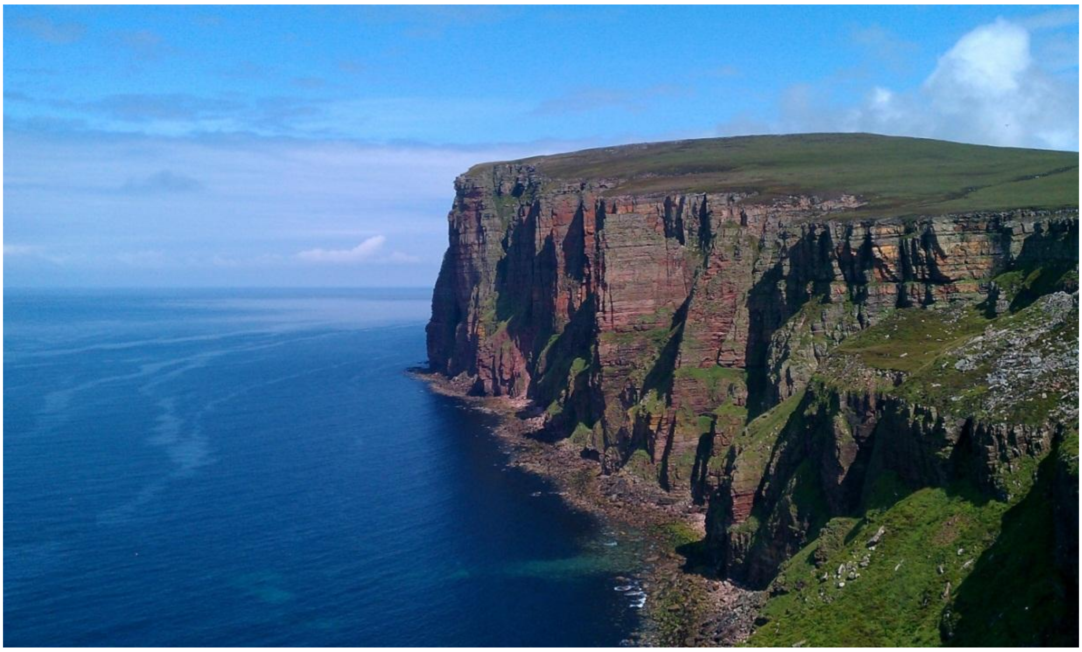
To my mother and father,



Frontispiece: The Old Red Sandstone of Orkney - looking northwest across the West Orkney Basin. Picture taken by the author.

Abstract

The West Orkney Basin is situated in a frontier hydrocarbon region of the United Kingdom Continental Shelf. This study presents a reappraisal of the tectono-stratigraphic development and petroleum potential of the basin, and is based on a recent compilation and partial reprocessing of all the available 2D reflection seismic for the area. Evidence for the presence of Devonian lacustrine source-rocks in the basin is demonstrated by the recognition of a syn-rift sequence overlying basement, which comprises two packages of contrasting seismic facies characteristics, which are correlateable to onshore Devonian source-rock and reservoir facies. The syn-rift sequence is truncated at unconformity; that is related to Late Carboniferous inversion of the Great Glen-Walls Boundary Fault system. A second major phase of rifting within the basin, with formation of new faults and reactivation of pre-existing Devonian faults, is interpreted to have initiated in the Late Permian and dwindled into the Early Jurassic. Subsequent extensive exhumation events occurred in the Mid-Jurassic to Early Cretaceous and Cenozoic, with removal of about 2.5 km of Upper Triassic to Lower Jurassic sediments and perhaps 0.5 to 1 km of Upper Cretaceous rocks. Timing of hydrocarbon generation from Devonian source-rocks was modelled using Genesis 1D basin-modelling software from Zetaware, and the results from this indicate that it most probable that the majority of hydrocarbon generation in the basin preceded the end of the second phase of rifting in the basin (Late Permian to Early Jurassic). Therefore, the major risks with play-concepts based on a Devonian source-rock are considered to be seal integrity during multiple and prolonged uplift events.

Acknowledgements

I am grateful to my supervisor Joe Cartwright, for giving me the opportunity to do this research project, and for his encouragement and patience. Joe made my time in Cardiff thoroughly enjoyable.

Many thanks to Premier Oil for funding the project, with a special mention to Tim Davies and Mike Norton, for their support and stimulating discussions on the West Orkney Basin.

Cheers to my comrades in the Cardiff 3D Lab for their banter and support, with special mentions to Bledd, Gwen, Chriss, Tuvie, Hamood and Ben.

Finally, without my families immense support, I certainly would not have got this far.

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Chapter 1

1 . Introduction

1.1 Rationale

The recognition that a portion of the oil accumulations within the Beatrice (Bailey et al. 1990) and Clair (Mark et al. 2008) oil fields (Fig 1.1) may have originated from Devonian lacustrine source rocks, has highlighted the potential of a Devonian source-rock play concept in the United Kingdom Continental Shelf (UKCS). However, reconstructions of the geographical extent of the Devonian/Orcadian Basin (Fig 1.1) in the UKCS are extremely poorly constrained, due to lack of well penetrations.

The West Orkney Basin (WOB) is situated on the western extremities of current understanding on Devonian extension and deposition (Fig 1.1). Mature Devonian source rocks outcrop in the east of the WOB on the Orkney Islands and along the NE coast of mainland UK. However, their western extent into the offshore areas of the WOB is unknown. Thus, the WOB represents a frontier hydrocarbon exploration opportunity.

In the 1980s, as petroleum exploration of the UKCS gathered momentum, there was considerable debate over the deep crustal structure of NW Scotland (e.g. Soper & Barber 1982; Butler & Coward 1984), which resulted in the advent of deep seismic profiling (BIRPS - British Institutions Reflection Profiling Syndicate) immediately offshore of the north coast of mainland UK. The seismic imaged (Fig 1.2) a series of eastward dipping sedimentary half-grabens (the WOB), overlying ambiguous dipping basement reflections, that appeared to sole out in the lower crust at 15 to 20 km (Brewer & Smythe 1984). The basement reflectivity was interpreted as the offshore continuation of Caledonian thrusts (Brewer & Smythe 1984; Enfield & Coward 1987; Snyder 1990). However, this contrasts significantly with onshore structural studies,

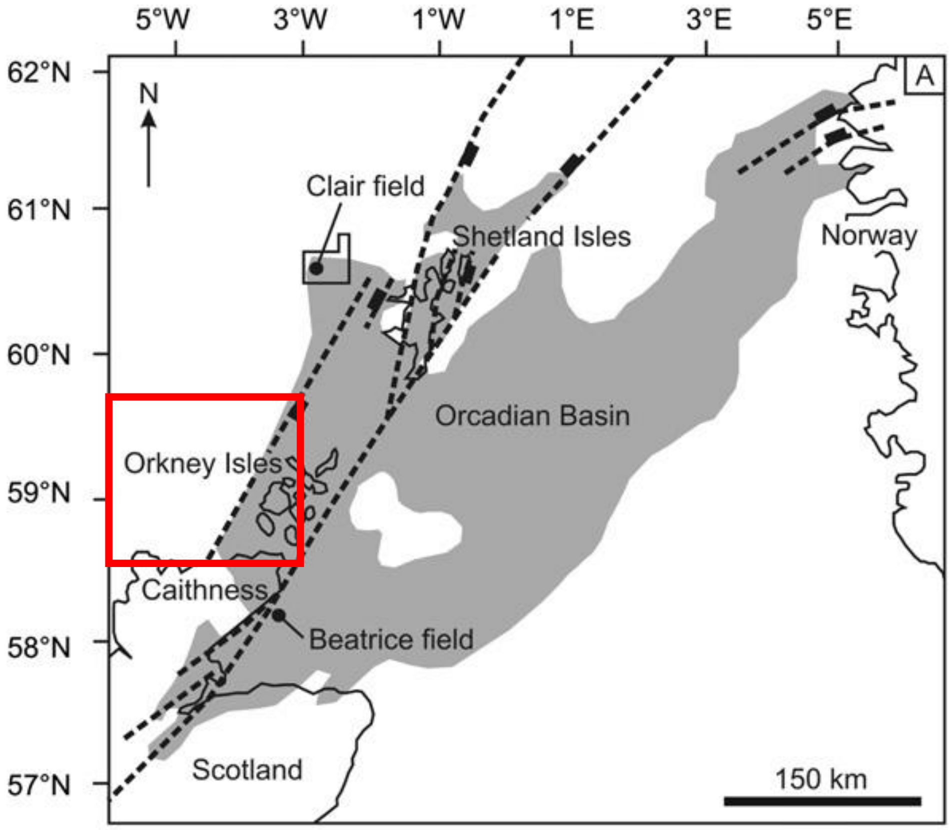

Figure 1-1. Map showing current understanding on the geographical extent of the Devonian/Orcadain Basin from Mark et al. (2008). Red box defines location of the WOB

which instead argued that the thrust belt is currently positioned in the upper crust, as a low angle detachment-dominated thrust system (Butler & Coward 1984).

It has also been proposed that the extensional faults bounding the half-grabens of the WOB trend parallel and directly correlate with specific intra-basement reflections, leading to an elaborate model of the area in which the WOB formed by the direct extensional reactivation of Caledonian thrusts (Brewer & Smythe 1984; Enfield & Coward 1987; Snyder 1990). This theory has been challenged by other authors (Holdsworth et al. 2001), who draw attention to the lack of evidence for reactivation in the onshore areas of the WOB. Therefore, the nature of basement reflectivity and its relationship to the overlying half-grabens of the WOB remains far from resolved.

Coward and Enfield (1987) used the deep seismic profiles from BIRPS and a commercial speculative seismic survey, to carry out the first structural mapping of the entire WOB (Fig 1.3). These authors interpreted the rift architecture of the basin to take the form of a simple fault system of long, interleaving curvilinear half-grabens (Fig 1.3) that contain three characteristic sedimentary sequences (Fig 1.4a). The sequences were interpreted to be mainly Devonian, being based on an inferred structural continuity between the offshore half grabens, Devonian outcrops on the Orkney Islands and sedimentary outliers along the northern coast of mainland UK, which some authors consider to be Devonian (e.g. Geikie 1878; Crampton & Curruthers 1914; Blackbourn 1981a, b; O'Reilly 1983; Coward et al. 1989; Seranne 1992; Holdsworth et al. 2001; Wilson et al. 2010). As a result, a single rift (Devonian) model was proposed for the formation of the WOB.

However, the results from two exploration wells drilled in the WOB in 1984 (well: 202/19-1) and 1991 (well: 202/18-1) disproved Coward and Enfield's (1987)

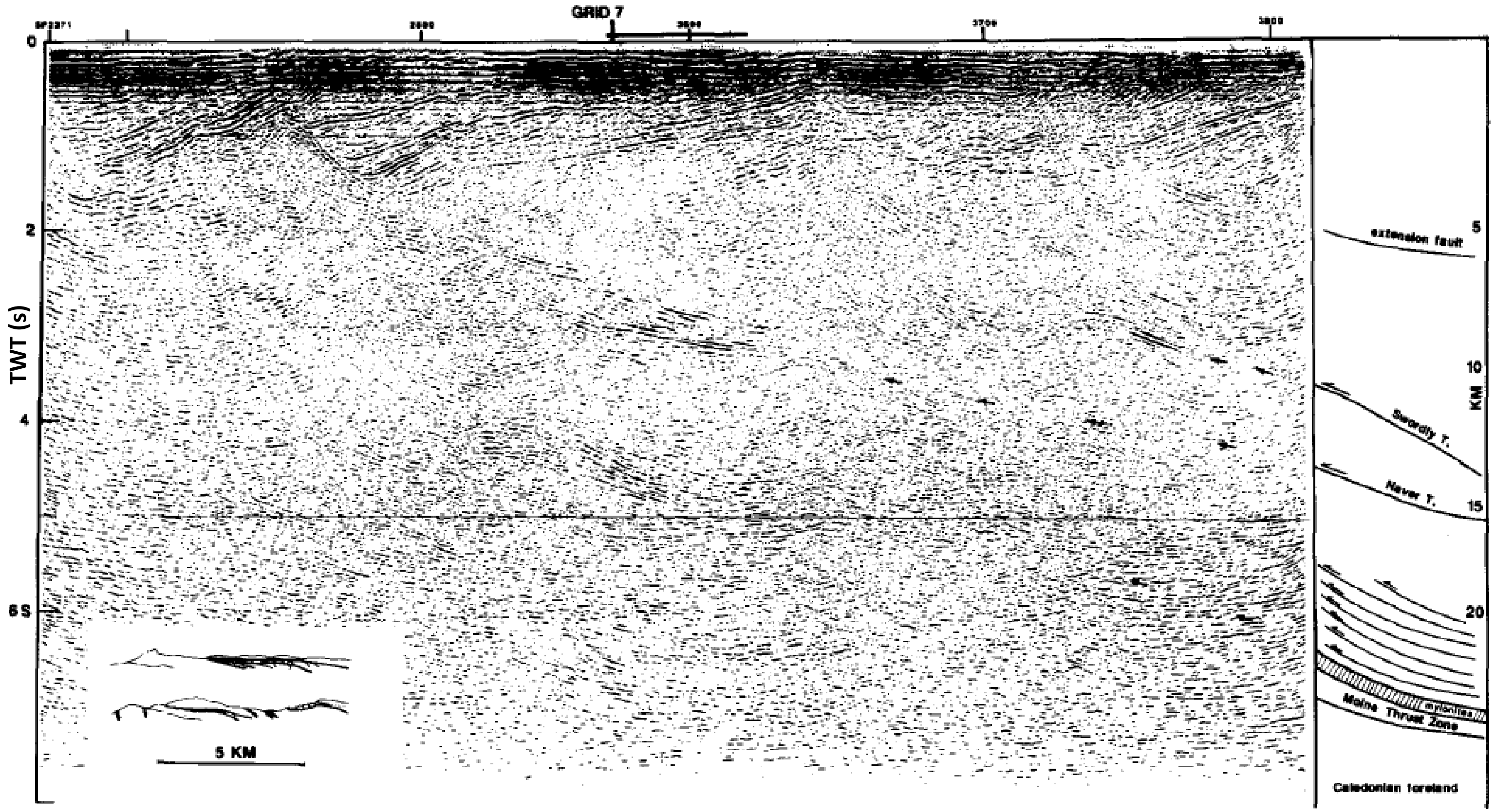

Figure 1-2. Snyder's (1990) interpretation of the DRUM deep seismic profile acquired by BIRPS across the southern portion of the West Orkney Basin.

deductions of a predominantly Devonian fill for the WOB, because over 3 km of entirely Permo-Triassic rocks were encountered (Hitchen et al. 1995), with no hydrocarbon shows. At the time, this seriously downgraded the pospectivity of the WOB, due to the major uncertainty over the presence of a mature Devonian source rock within the offshore areas of the basin. However, the wells were drilled in the west of the basin, and did not reach the top of the basement, and therefore the presence of a Devonian succession could not be completely ruled out.

Later studies (e.g. Earle et al. 1989, Stoker et al. 1993; Wilson et al. 2010) reinterpreted the ages of the three characteristic seismic sequences (Fig 1.4a) first distinguished by Coward and Enfield (1987), and proposed a Devonian age for only the lower westward thickening package, that is present in the east of the basin (Fig 4b). Similarly to previous studies (e.g. Coward and Enfield 1987), this new interpretation was again based only on the inferred structural continuity between Devonian outcrops onshore and the offshore half-grabens interpreted on seismic.

Understanding of the tectono-stratigraphic evolution of the WOB is critical for hydrocarbon prospectivity. However, it is challenging to interpret, due to the lack of preservation of rocks younger than Triassic within the basin. Wilson et al. (2010) carried out outcrop studies of post-Caledonian extensional patterns along the north coast of mainland UK and recognised fault systems consistent with NW-SE extension, that post-date outcropping Devonian ENE-WNW extensional faults (Coward et al. 1989; Johnstone & Mykura 1989). Although poorly demonstrated (e.g. Fig 1.4b), these authors also suggested that there is seismic evidence for Permo-Triassic NW-SE syn-extensional faulting in the offshore areas of the basin and related this to the NW-SE extensional fault systems they mapped onshore. As a result, a two stage rift model was proposed for the formation of the WOB (Devonian and Permo-Triassic).

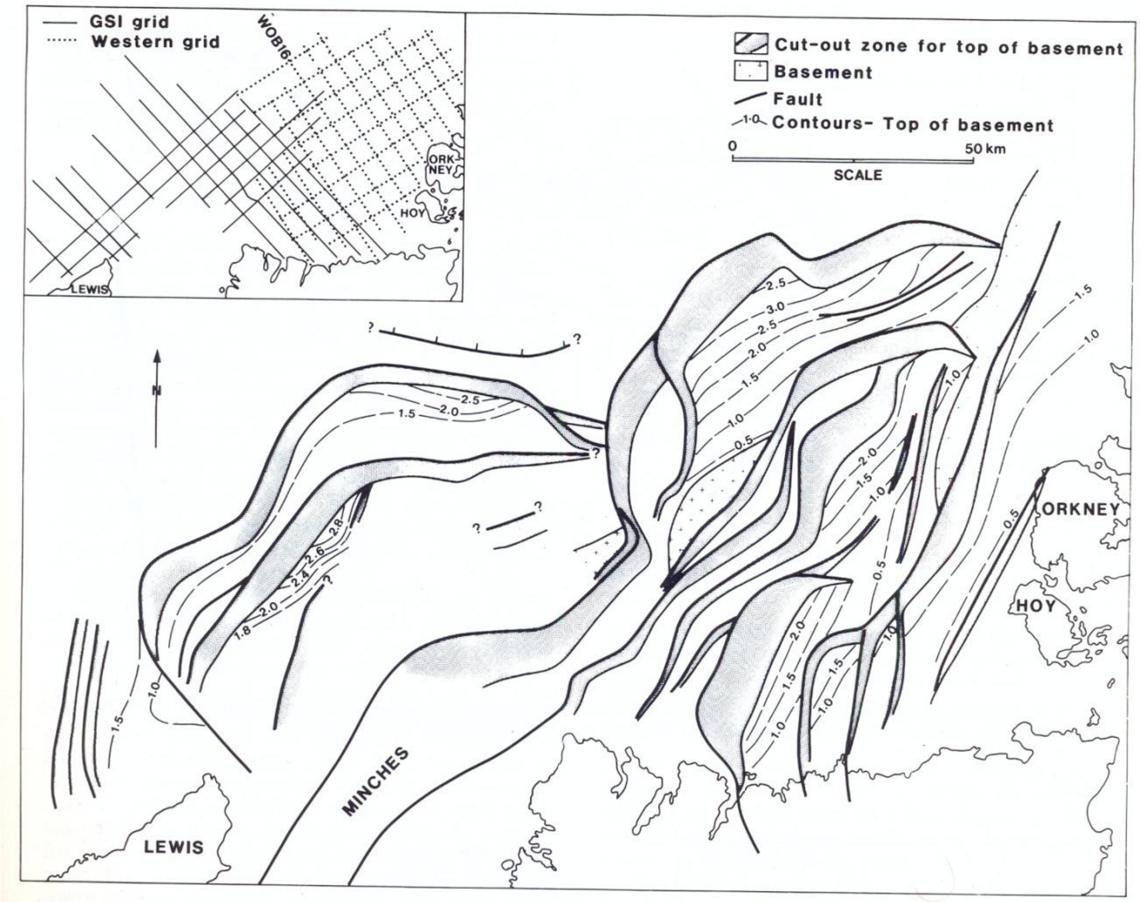

Figure 1-3. Coward and Enfield's (1987) interpretation of top-basement structure in the WOB

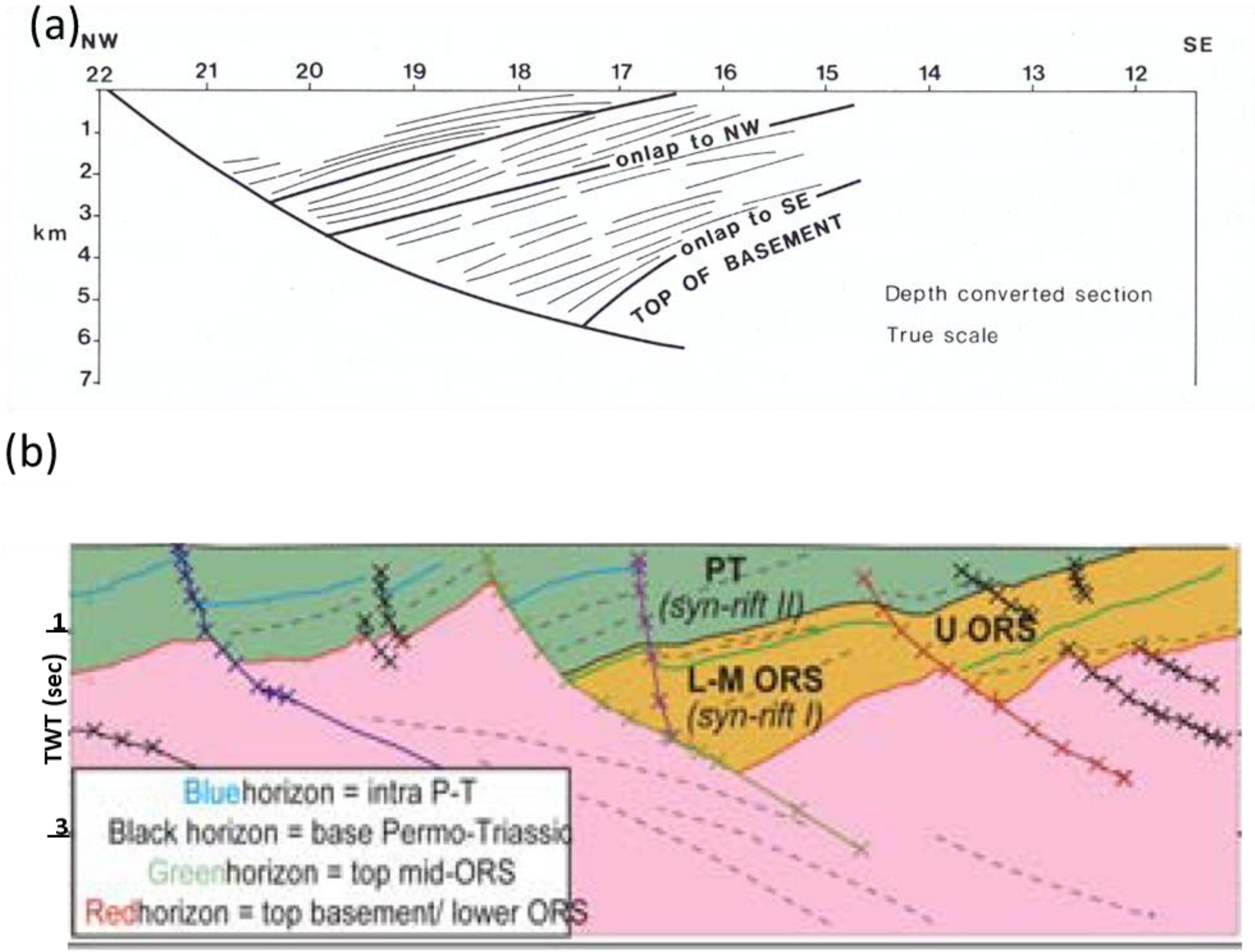

Figure 1-4. Coward and Enfield's (1987) interpretation of the three characteristic sequences within the WOB, in which they interpreted as entirely Devonian. Subsequence exploration wells drilled in the west of the WOB, encountered Permo-Triassic rocks. As a result later studies (e.g. Stocker et al. 1993; Wilson et al. 2010) interpreted Devonian to only be present in the east of the WOB, as shown in (b).

However, even if the onshore is representative of the offshore WOB as a whole, it is possible that the onshore NW-SE extensional fault array mapped by these authors could be associated with a number of post-Devonian rift events that may have occurred in this region of the NE Atlantic (e.g. Coward et al. 2003). Additionally, it is feasible that a significant portion of the faulting apparent on seismic within the WOB could have partly or entirely formed in later Mesozoic rift events. Furthermore, results from seismic mapping in the basin adjacent to the WOB (Solan Basin) led Booth et al. (1993) to suggest that the Permo-Triassic wedges visible on seismic within the West Orkney, Solan and Papa Basins, may not represent separate half-graben depocentres, but actually be the erosional remnants of a single large basin.

1.2 Research aim:

The aim of this PhD project is to provide a comprehensive review of the tectono-stratigraphic evolution of the WOB and the implications for hydrocarbon exploration. The research is sponsored by Premier Oil. Premier Oil acquired exploration acreage within the WOB in 2009, with a four year "drill or drop contract". They were the only operator present within the WOB during the period this research was carried out.

In order to fulfil the aim of the research project, this study utilises a much denser 2D seismic grid than was available to previous studies of the WOB (e.g. Enfield and Coward 1987). This new data compilation includes a number of profiles that have been recently reprocessed with modern processing algorithms. The reprocessing has better resolved the stratigraphy within the basin. For example, reflection continuity within the syn-rift sequences overlying basement in figures 4.3 to 4.5 (reprocessed versions) are much better imaged than in figures 4.8 and 4.9 (original processed versions). There has been no new seismic data acquired in the basin during this study.

The objectives of each chapter in the thesis are as follows:

Chapter 1 “Introduction”:

- Introduce the open research questions for the tectono-stratigraphic evolution of the WOB and the implications for hydrocarbon exploration.
- Introduce the objectives for addressing the open research questions.

Chapter 2 “Data and Methodologies”:

- Document the data and methodologies utilised during the PhD.

Chapter 3 “Basement reactivation in the development of rift basins: an example of reactivated Caledonide structures in the West Orkney Basin”:

- Provide a structural framework for basin analysis in chapter 4 and play fairway analysis in chapter 5.
- Re-appraisal on the deep crustal structure of offshore NW Scotland – offshore continuation of the Moine Thrust Belt
- Evaluate the fault reactivation hypothesis for the WOB – how have basement fabrics influenced rifting?

Chapter 4 “Tectono-stratigraphic Evolution of the West Orkney Basin”:

- Develop a new tectono-stratigraphic evolutionary model for the WOB – this is critical for revised / updated petroleum system analysis in chapter 5

- Redefine current understanding on the western extent of Devonian extension and deposition in the NE Atlantic - with specific focus on de-risking the presence of a Devonian succession (ultimately a Devonian source rock) in the offshore areas of the WOB.

Chapter 5 “Play fairway analysis”:

- Define play-fairyway
- Establish petroleum play concepts

Chapter 6 “Discussion implications for Hydrocarbon Exploration”:

- Model burial history and timing of hydrocarbon generation in the basin. Discuss the implications of this new research on the hydrocarbon prospectivity of the WOB – assess the potential for the entrapment and preservation of hydrocarbons within Devonian and younger sequences.

1.3 Regional tectonic setting

The Iapetus Ocean underwent progressive closure during the Silurian and Early Devonian, due to complex and protracted Caledonian Orogenic continental collision of Baltica, Laurentia and Eastern Avalonia. Closure and shortening across the Appalachians caused lateral expulsion of the European block, which was accommodated by left-lateral displacement along major transcurrent strike-slip faults, such as the Great Glen Fault Zone (Coward et al. 2003) (Fig 1.5 & 1.6). This closure created a new craton recognized as the ‘Old Red Sandstone Continent’, on which were deposited characteristic continental redbeds within intermontane basins, formed

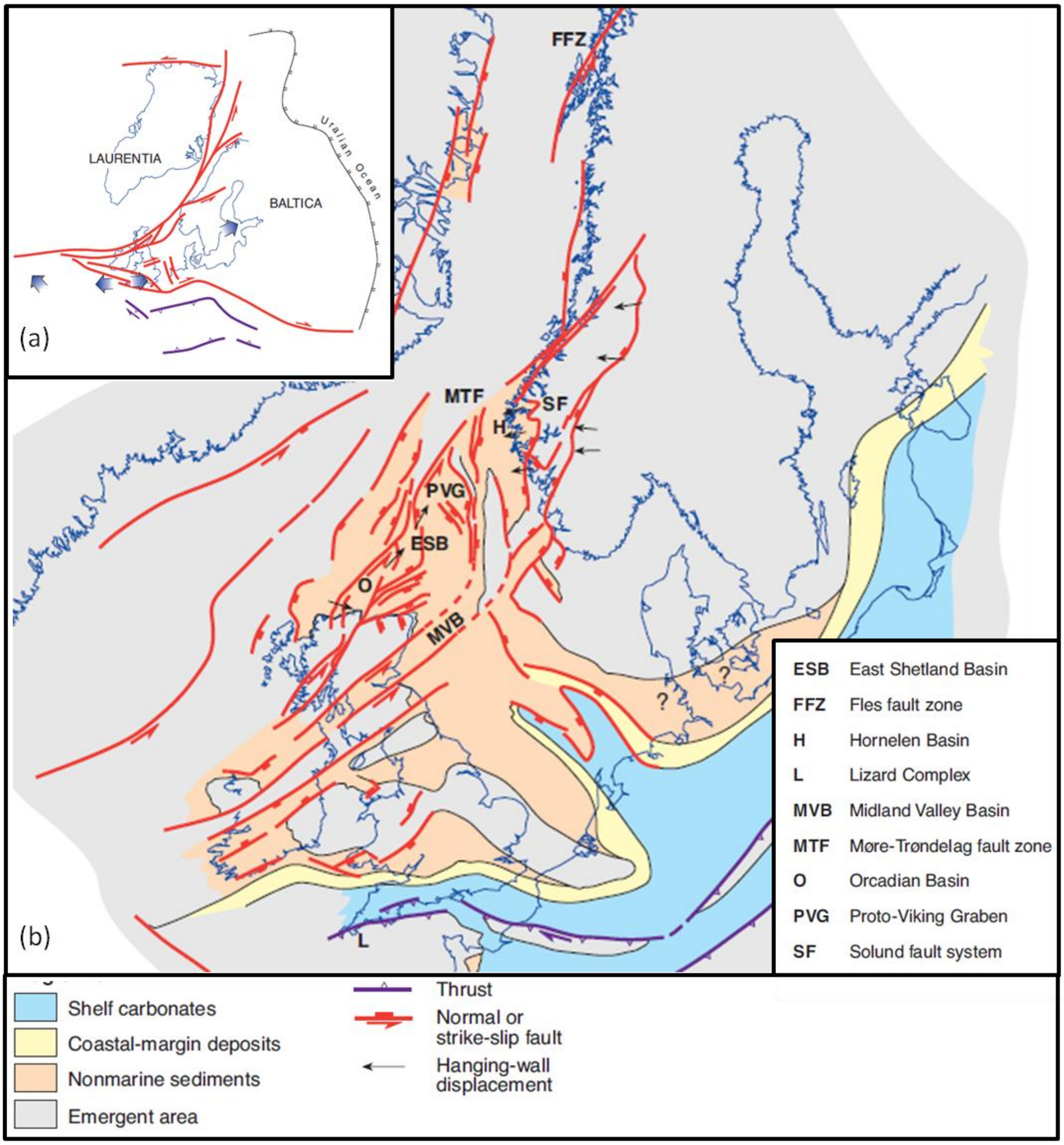

Figure 1-5. (a) Closure and shortening across the Appalachians caused lateral expulsion of the European block, which was accommodated by left-lateral displacement along major transcurrent strike-slip faults. (b) Devonian Palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures. Note, the western extent of the Orcadian Basin is poorly understood, and largely speculative (maps from Coward et al. 2003).

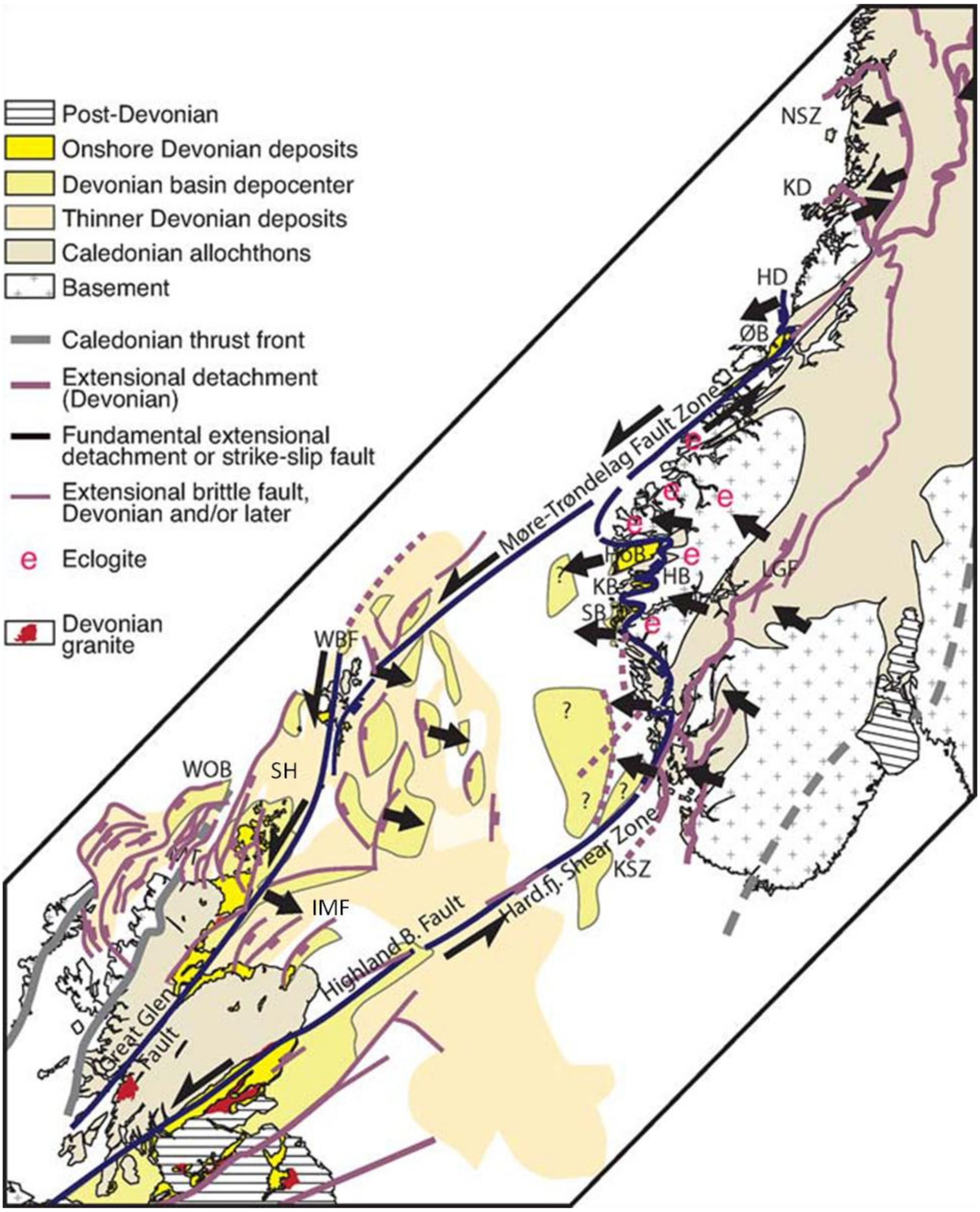

Figure 1-6. Diagram of a Devonian transtensional model for the formation of the Orcadian Basin (from Fossen 2010). Abbreviations – OB: Orcadian Basin, WOB: West Orkney Basin, WOS: West of Shetland Basin, IMF: Inner Moray Firth Basin, SH: Shetland High.

by possibly a combination of gravitational collapse of the over thickened Caledonian crust (McClay et al. 1986) and strike slip tectonics (Seranne 1992; Dewey 2003; Watts et al. 2007; Fossen 2010). It was in these basins that Devonian lacustrine source-rocks and associated reservoir facies were deposited (e.g. Fig 1.6). Paleomagnetic data indicate that the Old Red Sandstone continental landmass occupied a low-latitude between 15 and 30 S, where the climate was generally warm and arid to semi arid (Marshall & Hewett 2003).

The Highland Boundary (Coward et al. 1989; Dewey and Strachan, 2003; Watts et al 2007), More-Trondelag and Southern Uplands (Fossen 2010) Fault Zones, all show evidence for sinistral strike-slip movement in Devonian times (Fig 1.6). Seranne (1992) studied the spatial variation, distribution and extension direction of extensional and transcurrent tectonics in NW Europe, and suggested that these structures and Devonian basins may fit into a large scale sinistral-transtensional-overstep-pull-apart system (Fig 1.6).

The Devonian Orcadian rift system extends from the More-Trondelag Fault Zone in the north to the Highland Fault Zone in the south (Fig 1.6). Its exact geographic definition varies from study to study, as offshore reconstructions of basin boundaries are poorly defined, due to a lack of well penetrations into Devonian rock (Mark et al. 2008). The West Orkney Basin is located immediately off the north coast of Scotland (Coward and Enfield, 1987), being situated on the poorly defined western extremities of the larger Orcadian Basin, and thus, the extent of Devonian extension and deposition in the WOB is currently unknown, as Devonian rocks have not been penetrated by wells to the west of the Orkney Islands. Thus, the Devonian tectonic maps in figures 1.5 and 1.6 that illustrate Devonian rifts in this region are largely speculative.

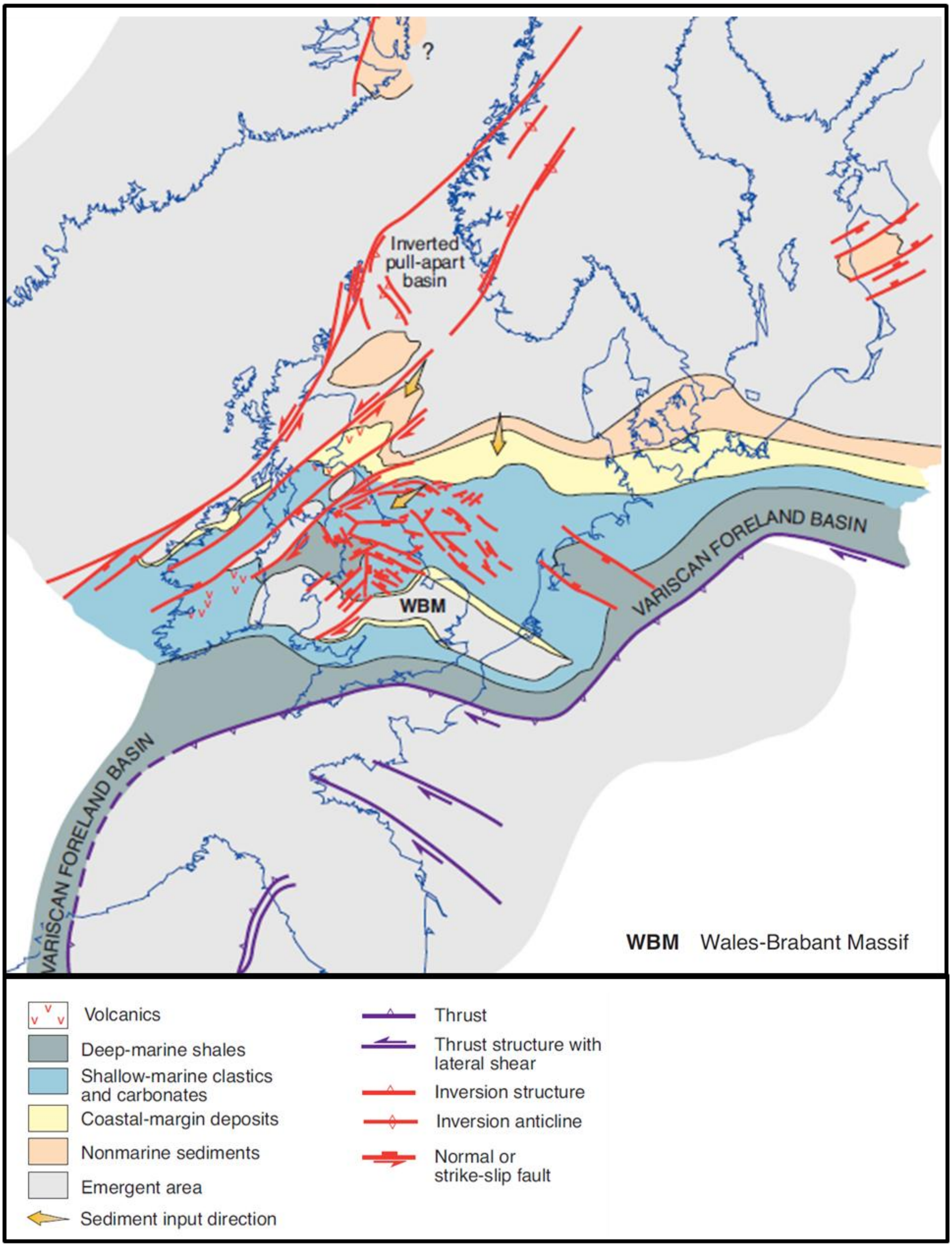

Figure 1-7. Early Carboniferous palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

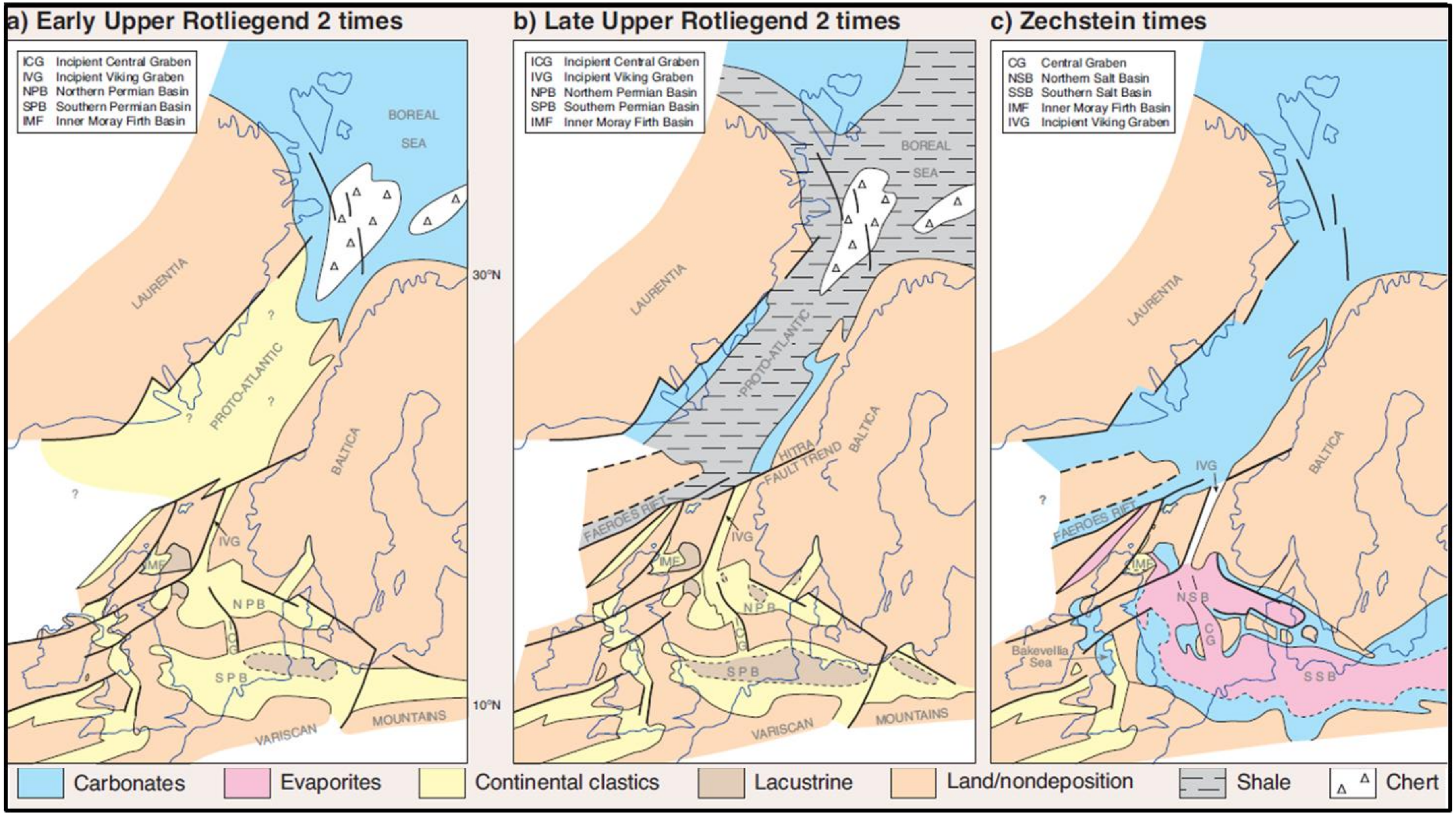

Figure 1-8. Conceptual palaeogeographical reconstruction of NW Europe during the Middle to Late Permian - illustrating the southwards advance of a Zechstein sea in the Late Permian (Glennie et al. 2003).

The transition from Devonian to Early Carboniferous in north-west Europe saw a change from mainly continental redbed deposition of the Devonian period to a more-varied fluvial, deltaic and marine sedimentation, as a result of marine transgression from the south over the Old Red Sandstone continent (Fig 1.7). Devonian left-lateral movements along the Midland-Valley and Great-Glen North Atlantic shear systems continued into the Early Carboniferous, and with a relative increase in sea-level, a general depositional pattern evolved with a deep marine siliclastic basin to the south of Britain and a dominantly fluvio-deltaic system towards the northern half of Britain (Bruce & Stemmerik 2003).

In the Late Carboniferous, the Variscan Orogeny resulted from collision of Laurasia and Gondwana, and formed a thin-skinned fold and thrust belt, which is distributed from southwest England to central German. Additionally, in Northern Britain and the northern North Sea, Devonian basins were inverted due to right-lateral movements along the Great-Glen Fault Zone and associated regional uplift (Coward et al. 2003). Late Carboniferous truncation of Devonian sequences has been reported from the Inner Moray Firth (Fig 1.6) (Marshall 1998) and around the Shetland High (Seranne 1992). Therefore, it is conceivable that the WOB also experienced uplift and erosion during the Late Carboniferous.

The supercontinent Pangea formed by the Early Permian, with much of north-western Europe, including the Faroe to West Orkney region, experiencing a time of intense igneous activity, with erosion or non-deposition, which is thought to be due to changes in regional stress pattern at the end of the Variscan Orogeny (Ziegler 1990; Ritchie et al. 2011). Throughout the remainder of the Permian, the Arctic rift system propagated towards the northern North Sea and western Ireland, via the Faroe-Shetland and West Orkney region (Fig 1.8) (Coward et al. 2003). However, the extent

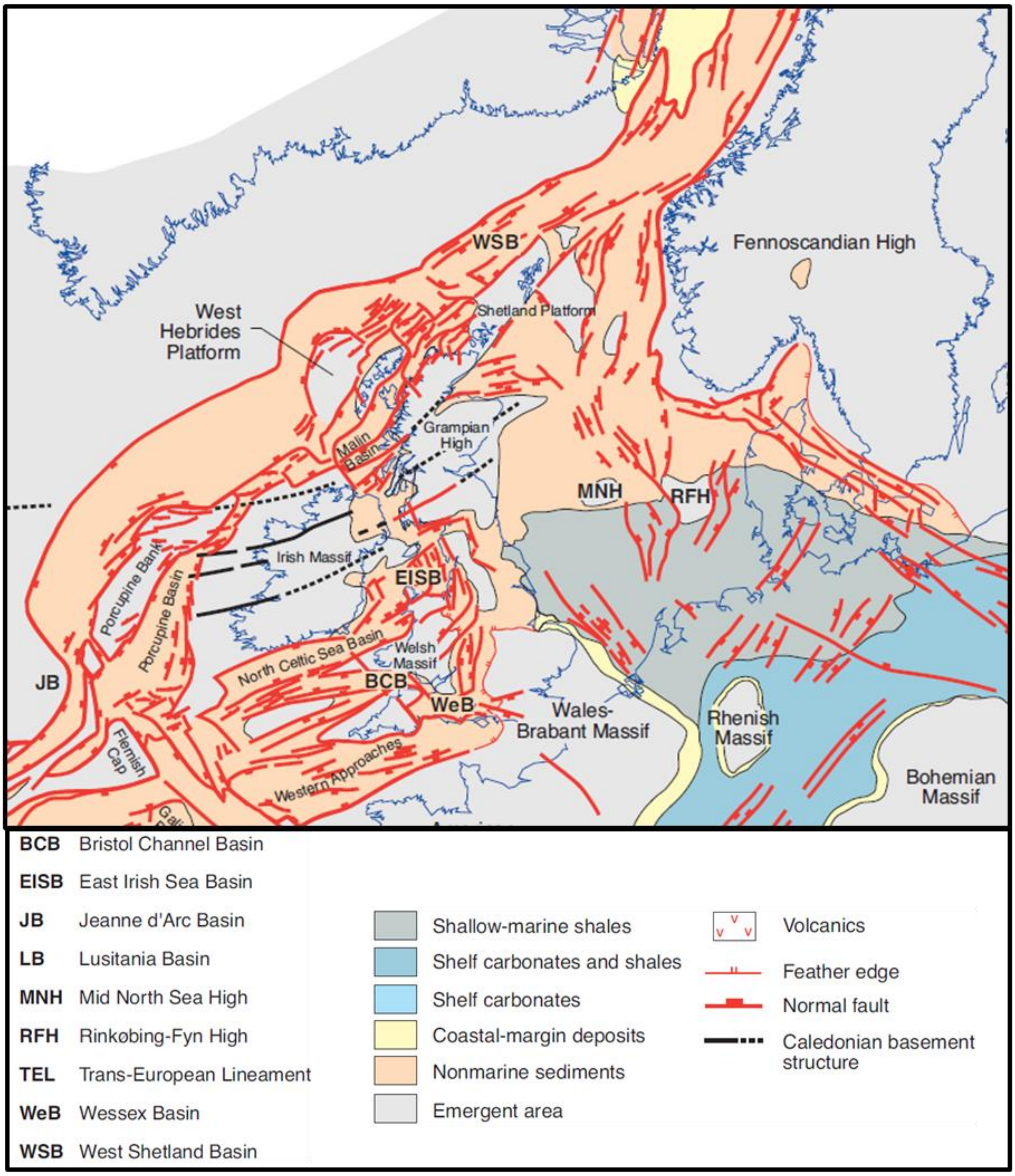

Figure 1-9. Triassic palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

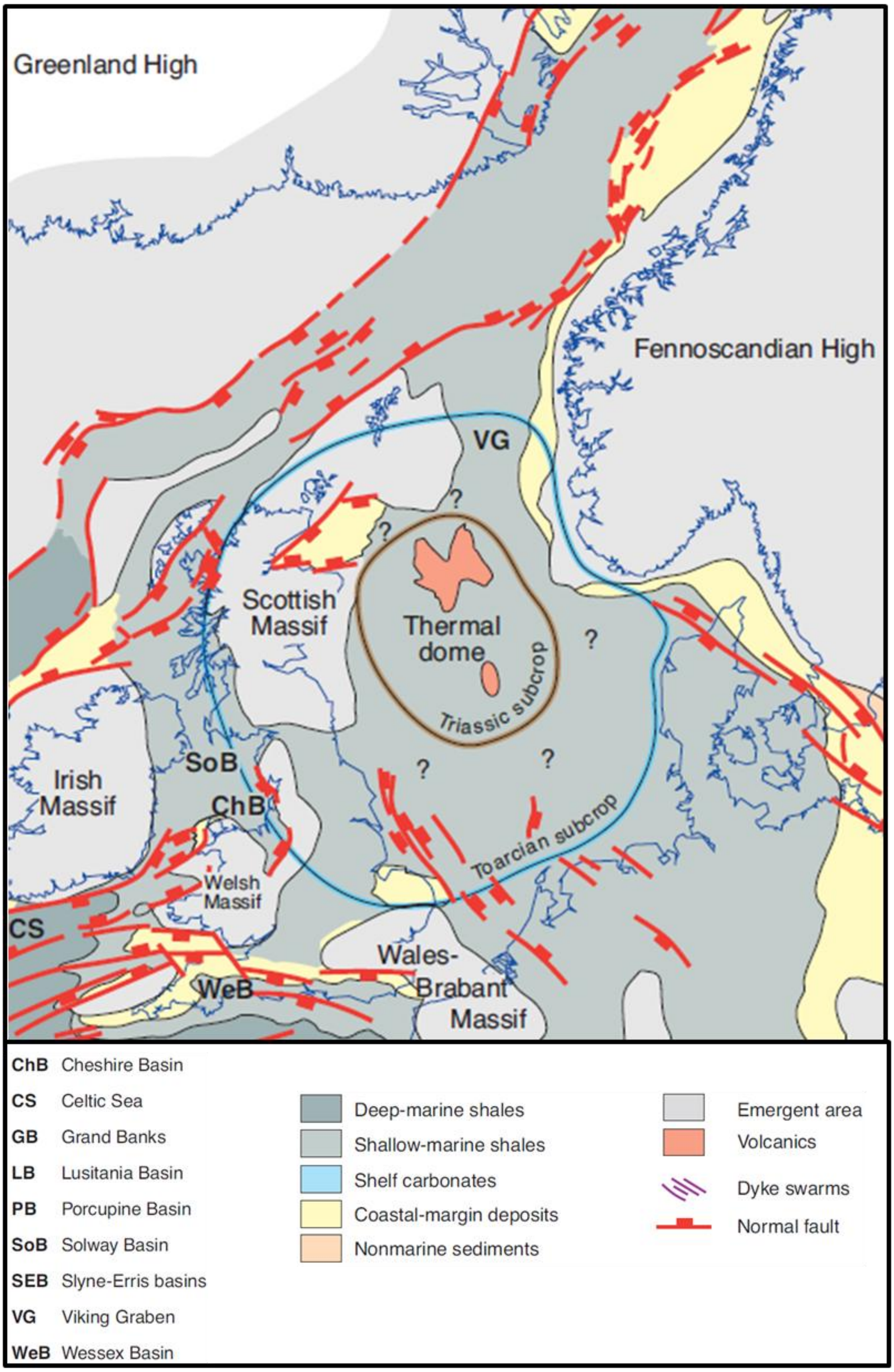

Figure 1-10. Early Jurassic palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003). The region affected by the postulated Mid-Jurassic North Sea hot-spot is also shown.

of Permian rifting in the Faroe-Shetland Basin is poorly understood, due to lack of well control. Generally, the Permian basins of NW Europe consist of a lower sequence known as the Rotliegend Group, that mainly comprises sandstones with local basal volcanics, and an upper sequence termed the Zechstein Group, consisting of evaporites and carbonates, with local clastics (Fig 1.8). These rocks were likely deposited in a latitudinal position similar to that of the present day Sahara desert. It is believed that the Zechstein Group was deposited as a result of a Late Permian glacio-eustatic rise in sea level, which resulted in southward marine transgression from the Artic and development of the Zechstein Sea across much of Northern Europe (Fig 1.8) (Glennie et al. 2003).

The transition from the Permian to Triassic in the NE Atlantic (Fig 1.9) was accompanied by continued rifting and regression of the Zechstein Sea (Coward et al. 2003). Triassic well correlations throughout the Faroe to West Orkney region imply that the Triassic depositional environment was dominantly fluvial and alluvial, with minor sheet flood deposits (Herries et al. 1999; Ritchie et al. 2011).

The Triassic-Jurassic shift saw rifting breach Pangea, with incipient ocean-floor spreading in the proto-Central Atlantic and the Tethys, resulting in marine transgression (Coward et al. 2003). Early Jurassic rifting has been documented as far north as the Hebrides Basin (Morton 1989) and offshore mid-Norway (Blystad et al. 1995) (Fig 1.10). However, its extent into the Faroe to West Orkney region is poorly understood, due to a lack of well control, and an extensive Mid Jurassic uplift and erosion event (Boot et al. 1993). This Mid Jurassic uplift event may have resulted from the region being underlain by a hot spot (Fig 1.10) (e.g. Underhill and Partington 1993).

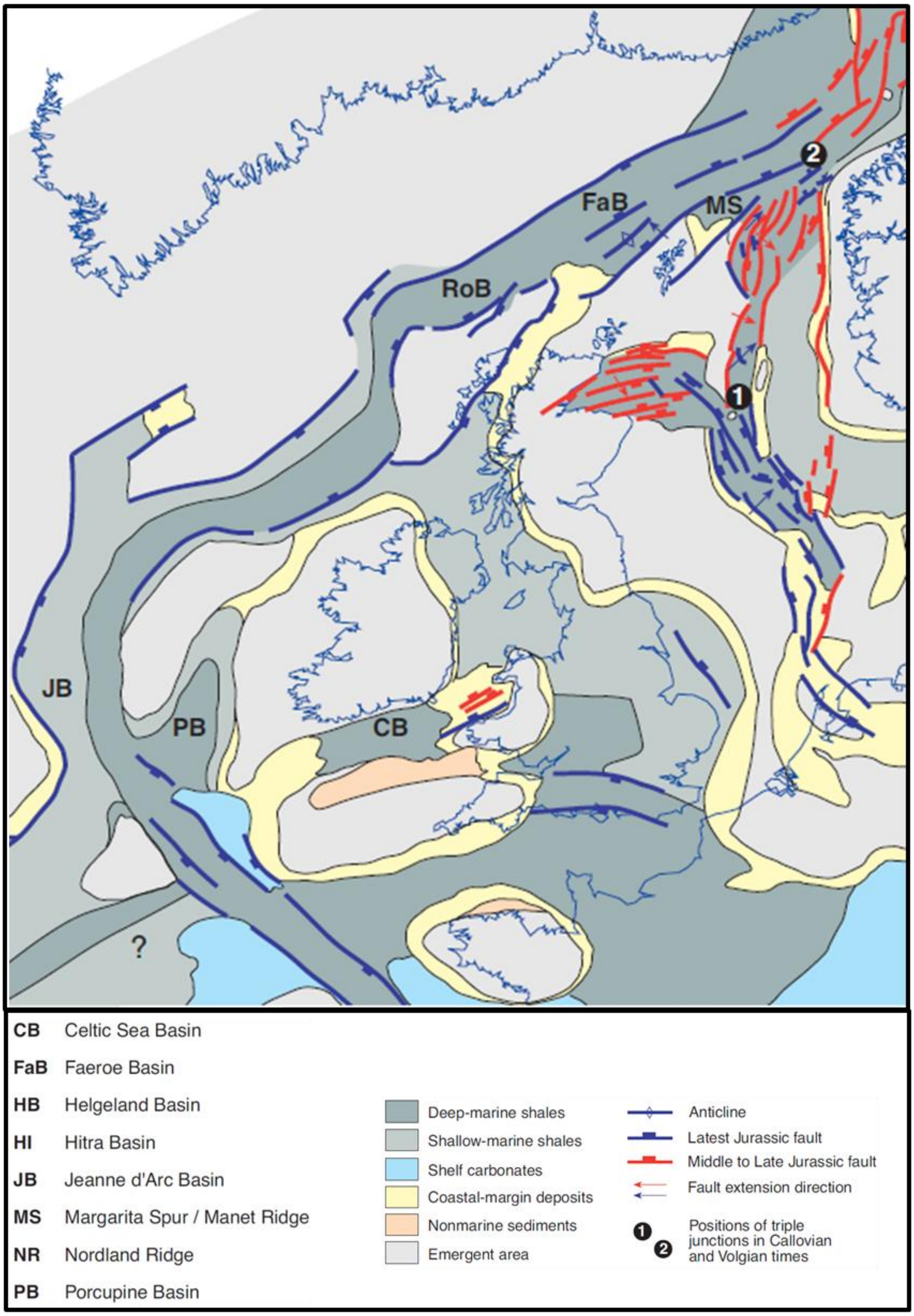

Figure 1-11. Late Jurassic palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

Renewed east-west oriented rifting in the Late Jurassic (Fig 1.11) is very well documented in the North Sea (e.g. Doré 1991), Halten Terrace (Brekke 2000), East Greenland (Surlyk 1991) and the Porcupine Basin (Tate et al. 1993). In contrast, it is unclear whether Late Jurassic rifting occurred within the Faroe to West Orkney region, because the Late Jurassic succession that has been encountered in wells is only a few hundred metres thick, with minor thickness variations (Dean et al. 1999).

By the Early Cretaceous the Atlantic Ocean had propagated into the region between the Azores fracture zone and the Biscay region (Fig 1.12). Major NW-SE Cretaceous rifting affected the Faroe-Shetland Basin, which is broadly interpreted to have occurred in three phases: (1) Valanginian-Barremian, (2) Aptian-Albian and (3) Campanian-Maastrichtian (Booth et al. 1993; Dean et al. 1999). It is unknown if a Cretaceous rift phase occurred in the WOB, due to the non-preservation of rocks younger than Triassic in the basin. During the Late Cretaceous, rift activity was relatively quiescent, with the majority of the North Atlantic basins experiencing passive thermal subsidence, with associated marine transgression and deposition of thick chalk sequences and deep marine shales (Fig 1.13).

In association with continental break-up in the Early Cenozoic, voluminous amounts of igneous material were emplaced within the Atlantic Margin basins (Fig 1.14). Palaeocene rifting in the Faroe-Shetland Basin was contemporaneous with regional uplift, high heat flows and widespread erosion of the Scottish Highlands (Dean et al. 1999), which resulted from either crustal under-plating of the Icelandic hotspot (White & Lovell, 1997; Jones et al. 2002) or intra-plate compression, driven by plate boundary forces (Holford et al. 2009). Throughout the remainder of the Cenozoic, the NE Atlantic experienced continued pulses of uplift, associated with igneous underplating and North Atlantic sea floor spreading (Stoker et al. 2010) (Fig 1.15).

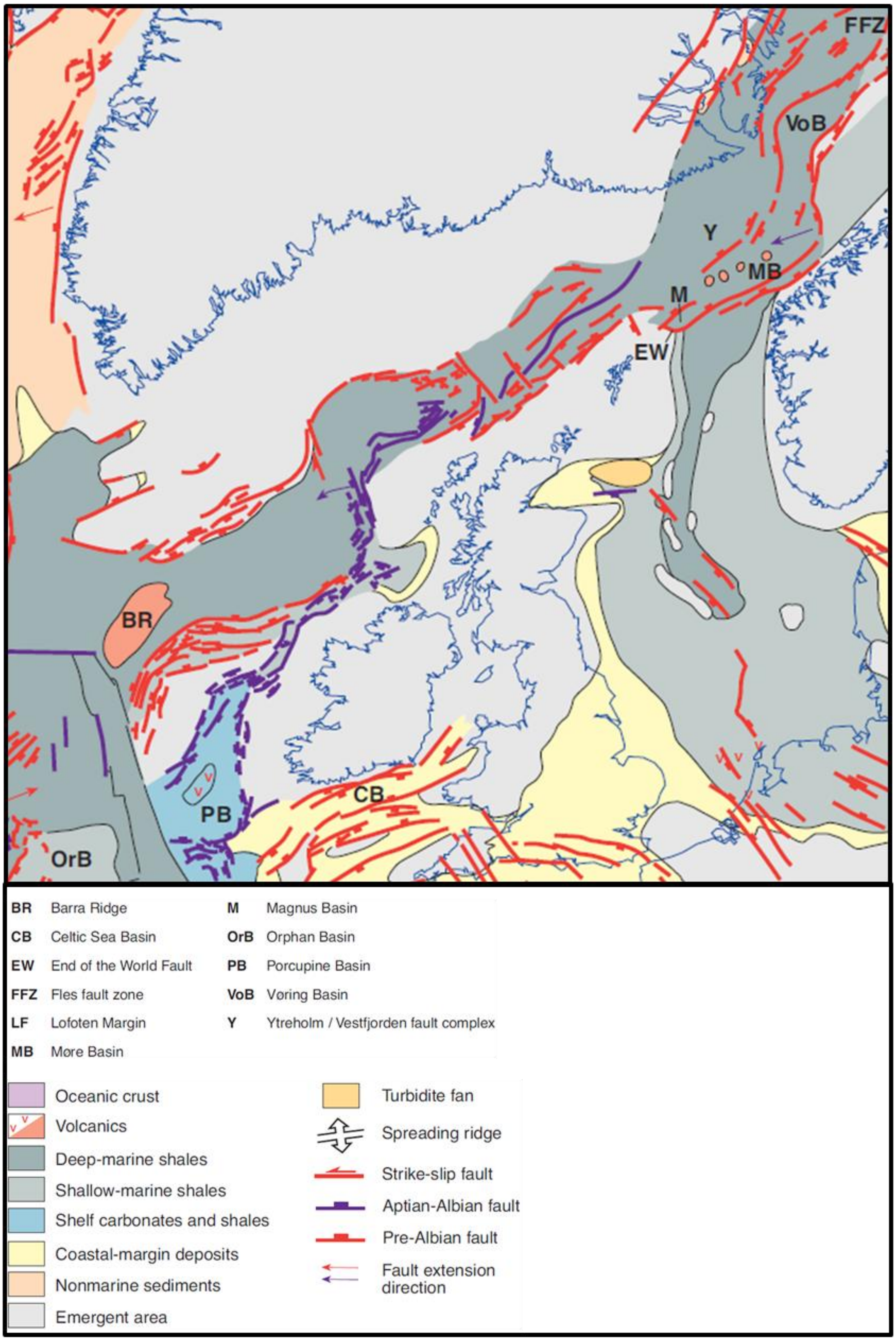

Figure 1-12. Early Cretaceous palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

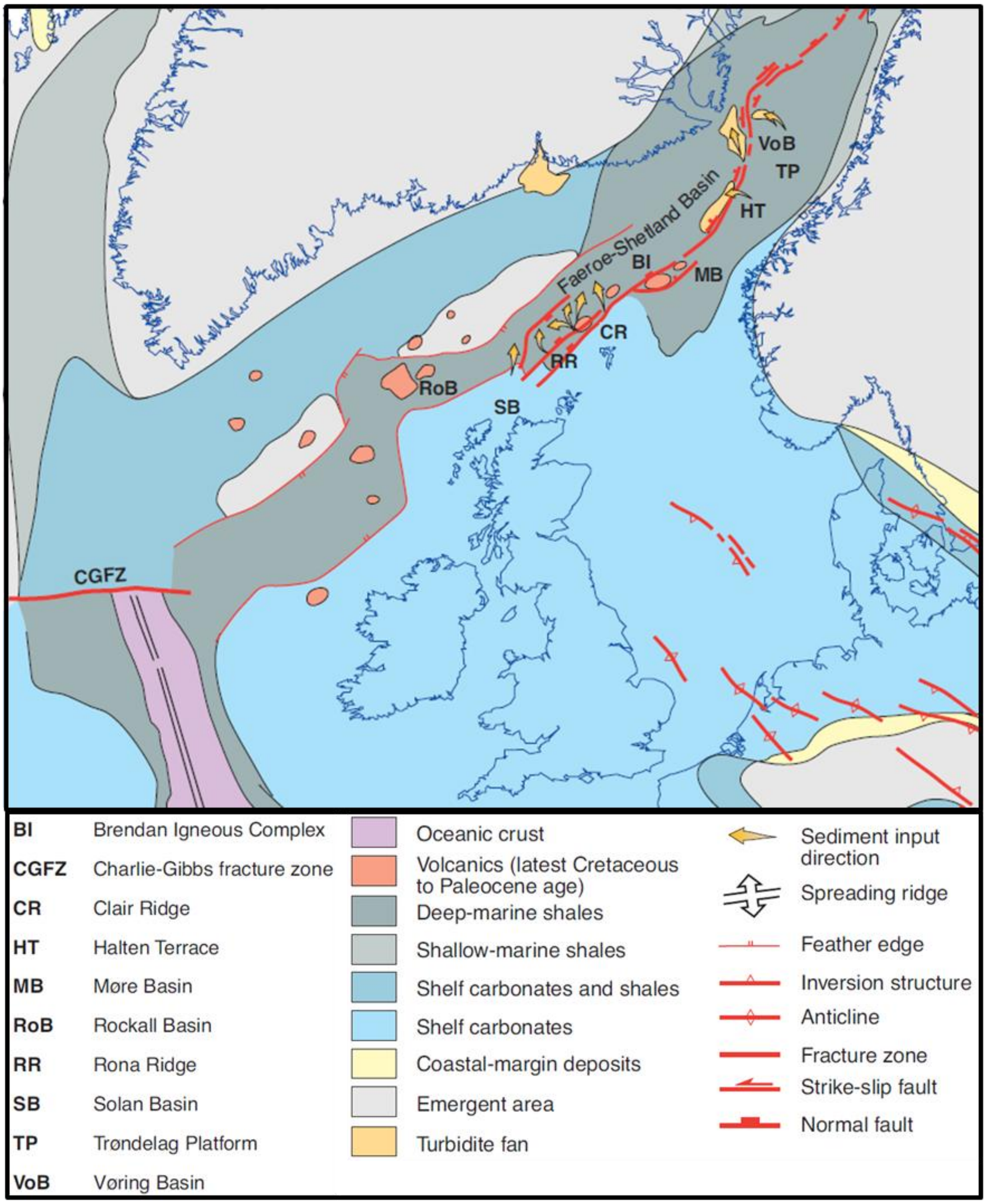

Figure 1-13. Late Cretaceous palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

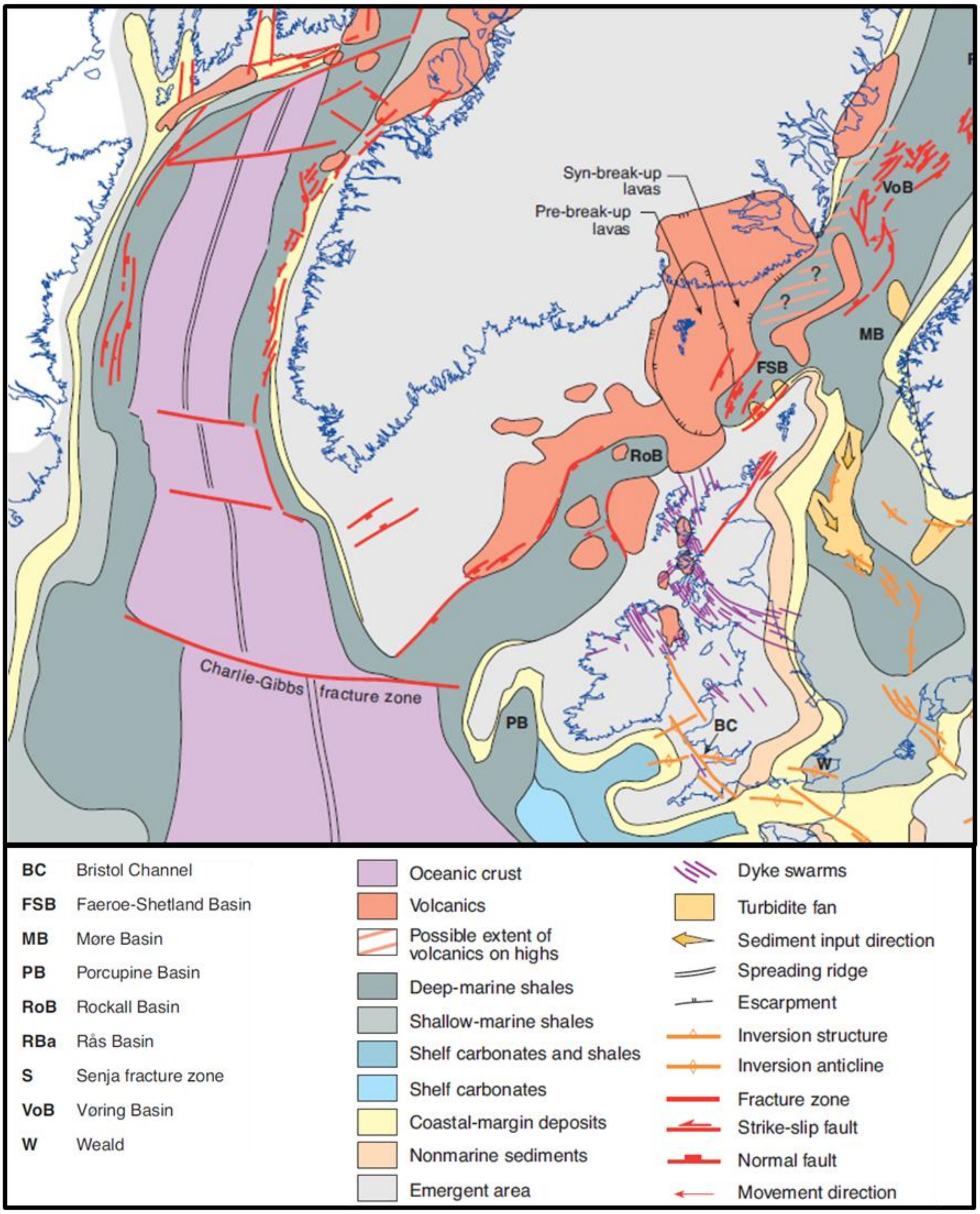

Figure 1-14. Paleocene palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

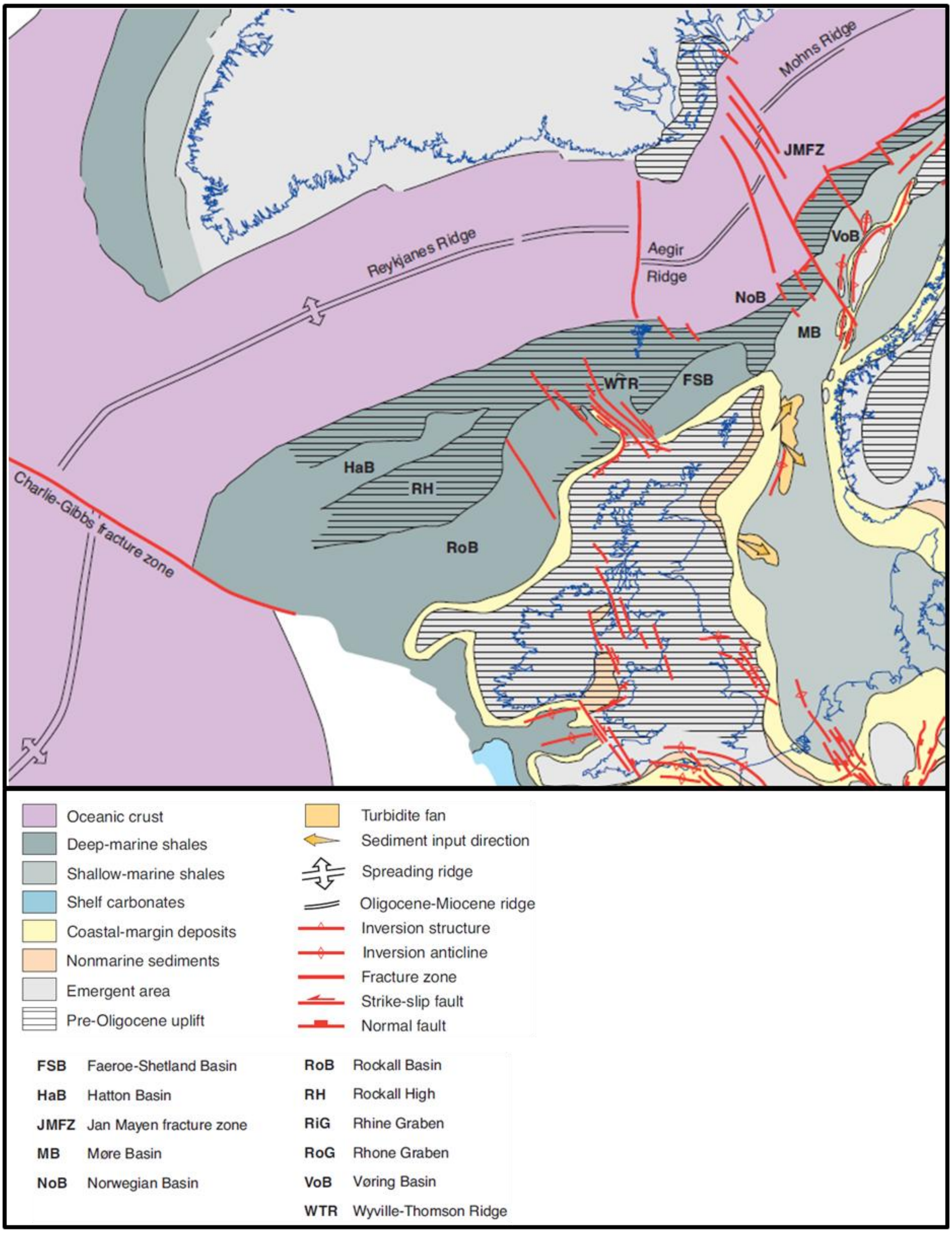

Figure 1-15. Oligocene palaeogeographical reconstruction of NW Europe, illustrating palaeofacies and active structures (Coward et al. 2003).

Chapter 2

2 Data and Methodology

2.1 Introduction

The present study was conducted using a dataset that includes 2D multichannel reflection seismic, wireline data, well reports and outcrop data. This chapter aims to provide a brief overview of the dataset and the methodology used in interpreting the data.

2.2 Data set

2.2.1 2D Multichannel refection seismic

The structure and stratigraphy of the offshore portion of the WOB was analysed on a 2D seismic dataset (Fig 2.1) consisting of three deep seismic profiles (from Snyder & Hobbs 2000) immediately off the north coast of Scotland and four different commercial seismic surveys (acquired in the 1980s and 1990s) that cover the entire basin. The total line kilometre length of the profiles within the WOB available to this study was about 10000 km, giving an average line spacing of 5 km in the WOB.

All of the seismic data used in this study has had various various processing algorithms applied. The purpose of seismic processing is to manipulate the acquired data into an image that can be used to infer the sub-surface structure. Only minimal processing would be required if we had a perfect acquisition system. Processing consists of the application of a series of computer routines to the acquired data, which is guided by a processing geophysicist.

The processing applications in this study involved NMO (normal moveout correction) velocity analysis, noise attenuation, de-multiple and pre-stack time migration. Generally this procedure can be said to enhance signal at the expense of noise, provide velocity information of the rocks, and collapse diffractions and place dipping events in their true subsurface locations (migration).

Industry led seismic reprocessing by Spectrum, of a total of 579 km line length of the commercial seismic profiles was carried out in 2012 and the results were made available for this study. The objective of the reprocessing was to improve definition of intra-Devonian reflections within the fill of the half-grabens.

The quality of the seismic data is diverse and reflects not only the date of acquisition, but also the acquisition, processing parameters and purpose of the survey at the time it was obtained. For example, the three deep seismic profiles (from Snyder & Hobbs 2000) acquired immediately off the north coast of Scotland were designed for imaging deep crustal structure, whereas the shallow commercial data was acquired for hydrocarbon exploration purposes. The poorest quality of imaging is located near to the onshore (within 15 km), which makes it highly difficult to correlate the seismic with onshore stratigraphy. Variations in data quality and its implications to the study are discussed throughout the thesis in greater detail.

In order to gain understating on the post-Triassic evolution of the WOB, this study also had access to a large 2D seismic dataset (about 20,000 km) in the adjacent Faroe-Shetland Basins to the northwest of the WOB (Fig 2.1), where Mesozoic and Tertiary sediments are preserved. This data comprised different vintages of 1990s seismic and therefore varies in quality.

2.2.2 Wells

Data from hydrocarbon exploration wells used in this study is listed in the table below:

Well	Basin location	logs	Final well Report available	Bio-strat data available	Time-depth data available
202/19-1	WOB	Composite, gamma, resistivity, sonic, density	Yes	No	Check-shot
202/18-1	WOB	Composite, gamma, resistivity, sonic, density	Yes	No	Check-shot
202/12-1	Rona Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
202/8-1	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
202/2-1	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
202/3-1A	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
202/3-2	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
202/3a-3	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
204/30-1	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot
205/26a-2	Solan Basin	Composite, gamma, resistivity, sonic, density	Yes	Yes	Check-shot

2.2.3 Outcrop

Devonian rocks of the Orcadian Basin outcrop on Orkney (Fig 2.1). A total of three weeks field work was undertaken in Orkney during this study. The purpose of the field excursion was to conduct a reconnaissance survey of Devonian outcrops. The outcrops can be used as analogues for helping constrain depositional models for the WOB.

2.3 Methods

2.3.1 Seismic interpretation

Seismic reflection interpretation is the most widely used and well-known technique in basin analysis (Allen & Allen 2005). Seismic sections are produced to reveal sub-surface details of geological structures on scales from tens of metres to the entire lithosphere. This is achieved from seismic reflection surveying; where seismic energy pulses are reflected from subsurface interfaces and recorded at near-normal incident at the surface (Kearey et al. 2002).

The speed of a seismic wave is governed by the acoustic impedance of the medium in which they are travelling. The acoustic impedance, Z, is defined by the equation:

$$Z = V \rho$$

Where V is the seismic wave velocity and ρ is the density of the rock. Reflection surveys are most commonly carried out in areas of shallowly dipping sedimentary sequences. In such situations, acoustic impedance varies with depth, due to the differing physical properties of the individual rock layers. Usually seismic velocity increases with depth due to the effects of rock digenesis and compaction (Telford & Sheriff 1990).

Seismic resolution is defined as the ability to distinguish separate features - the minimum distance between two features so that the two can be defined separately rather than as one. Vertical resolution is governed by Rayleigh Criterion, where the seismic "measure" is a wavelength. In order for two nearby reflective interfaces to be distinguished well, they have to be about 1/4 wavelength in thickness (Rayleigh Criterion). This is also the thickness where interpretation criteria change, that is, for smaller thicknesses than 1/4 wavelength, the amplitude is used to judge the bed thickness, and for thicknesses larger than 1/4 wavelength, the wave shape is used to judge bed thickness. The assumptions are the seismic signal has one frequency and that seismic waves travel at one velocity. Additionally, vertical resolution decreases with the distance travelled (hence depth) by the ray because attenuation robs the signal of the higher frequency components more readily (Kearey et al. 2006)

Generally, the seismic dataset used by this study has relatively low frequencies of about 15 to 25 Hz and wave lengths of about 250 m (Velocity = frequency x wavelength), and thus the vertical resolution is about 50 to 100 m. Uncertainty in vertical resolution, even at significant depths, is generally deemed negligible, when compared to the scale of the tectono-stratigraphic sequences that are of interest. The horizontal resolution of the seismic, defined by the Fresnel Zone (Telford & Sheriff 1990) is considered to be insignificant compared to line spacing (kilometres), and can be ignored.

Seismic interpretation software (IHS-Kingdom) was used for evaluating the tectono-stratigraphic evolution of the WOB, by the determination of tectono-stratigraphic sequences; defined here informally as sequences denoting seismically recognisable packages of distinctive reflection character. Where possible, boundaries to sequences where described using well-established seismic stratigraphy techniques (e.g.

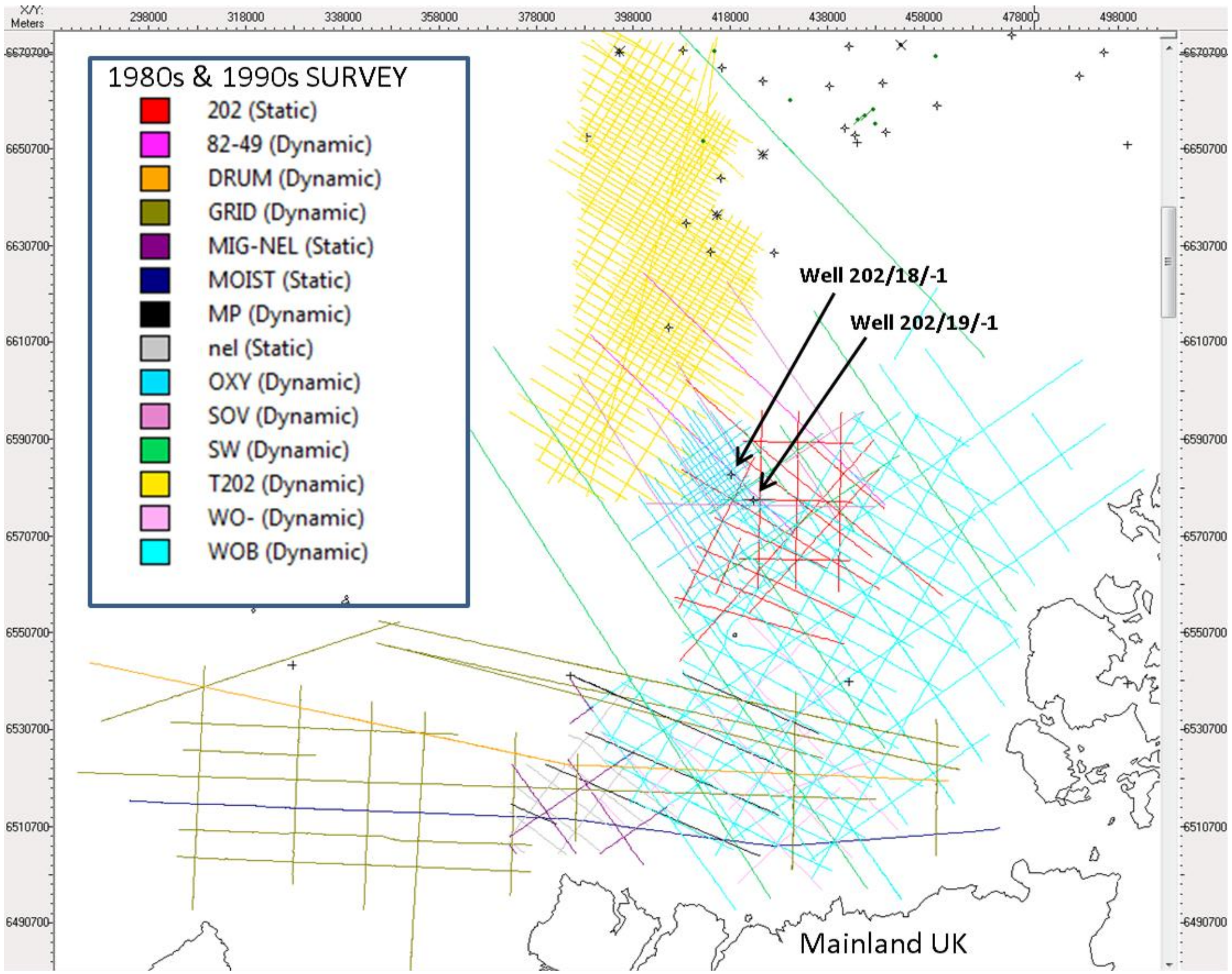

Figure 2-1. The present study was conducted using a dataset that includes 2D multichannel reflection seismic, wireline data, well reports and outcrop data (from Orkney). The total line kilometre length of the profiles within the WOB was about 10000 km. This study also had access to a large 2D seismic dataset (about 20,000 km) in the adjacent Faroe-Shetland Basins.

Catuneanu 2006) - through the identification of seismic reflectors geometries (e.g. onlap, downlap, erosional truncation).

Where seismic sequences were faulted, the position of hangingwall and footwall cut-offs were interpreted with reasonable precision by picking systematic alignments of stratal cut-offs and fault plane reflections (e.g. Prosser 1993).

One advantage of having four separate commercial surveys available in the combined dataset of this study is that it facilitated the recognition of acquisition and processing artefacts. This is most important in Chapter 3, where the large variation in acquisition and processing techniques between the different surveys allowed for the interpretation and lateral continuity of intra-basement reflections to be rigorously tested, since velocity models and stacking/migration algorithms were unique to each survey. By comparing intra-basement imaging on closely adjacent lines, it was possible to build confidence in the continuity of these reflections as they were correlated through the grid.

Depth conversion was carried out using a layer cake model, with each layer being assigned an interval velocity, as opposed to using an average velocity for the entire sedimentary fill within the basin. Velocity information for Permo-Triassic sediments within the half grabens was based on time-depth data from check-shot surveys in WOB exploration wells 202:19-1 and 202:18-1. Constant interval velocities of 6200 ms^{-1}, 5000 ms^{-1} and 4400 ms^{-1} were utilised for basement, Lower to Lower Middle and Upper Middle to Upper Devonian sequences respectively. These values are based on the results from velocity analysis that was conducted by Spectrum, during reprocessing of the data.

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Chapter 3

3 Basement reactivation in the development of rift basins: an example of reactivated Caledonide structures in the West Orkney Basin

Abstract:

The West Orkney Basin (WOB) is a poorly studied Palaeozoic and Mesozoic rift basin that overlies a highly seismic-reflective Caledonian orogenic basement terrane. This study presents a novel approach of using 2D seismic data, to map individual intra-basement reflection packages and their relationship to overlying normal faults in the WOB. Rift structures form complex discordant and concordant relationships with basement structures. Restoration of basement fabrics to their pre-extensional geometry indicates that the reactivation of basement structures as normal faults has only occurred where the pre-extensional-dip of basement structures is greater than 30°. The relatively high density of relay zones mapped in the WOB, are proposed to be the result of the rift-system forming a partially exploitive relationship with basement fabrics, where extension has been accommodated between segments that have reactivated basement fabrics and segments that have not.

3.1 Introduction

The Moine Thrust Belt of northern Scotland is an extensively studied foreland propagating thrust system, yet the deep crustal structure of the region and its influence on rift-basin development in the West Orkney Basin (WOB), remains far from resolved (Butler 2010). Onshore relationships favour the Moine to be a low-angle detachment dominated thrust system, that presently soles out in the upper crust (Butler & Coward 1984), whereas immediately offshore, deep seismic reflection profiling has imaged ambiguous steeply-dipping reflections throughout the majority of the crust, suggesting that thrusts may detach into the lower crust (e.g. Brewer & Smythe 1984; Enfield and Coward 1987; Snyder 1990). However, the latter

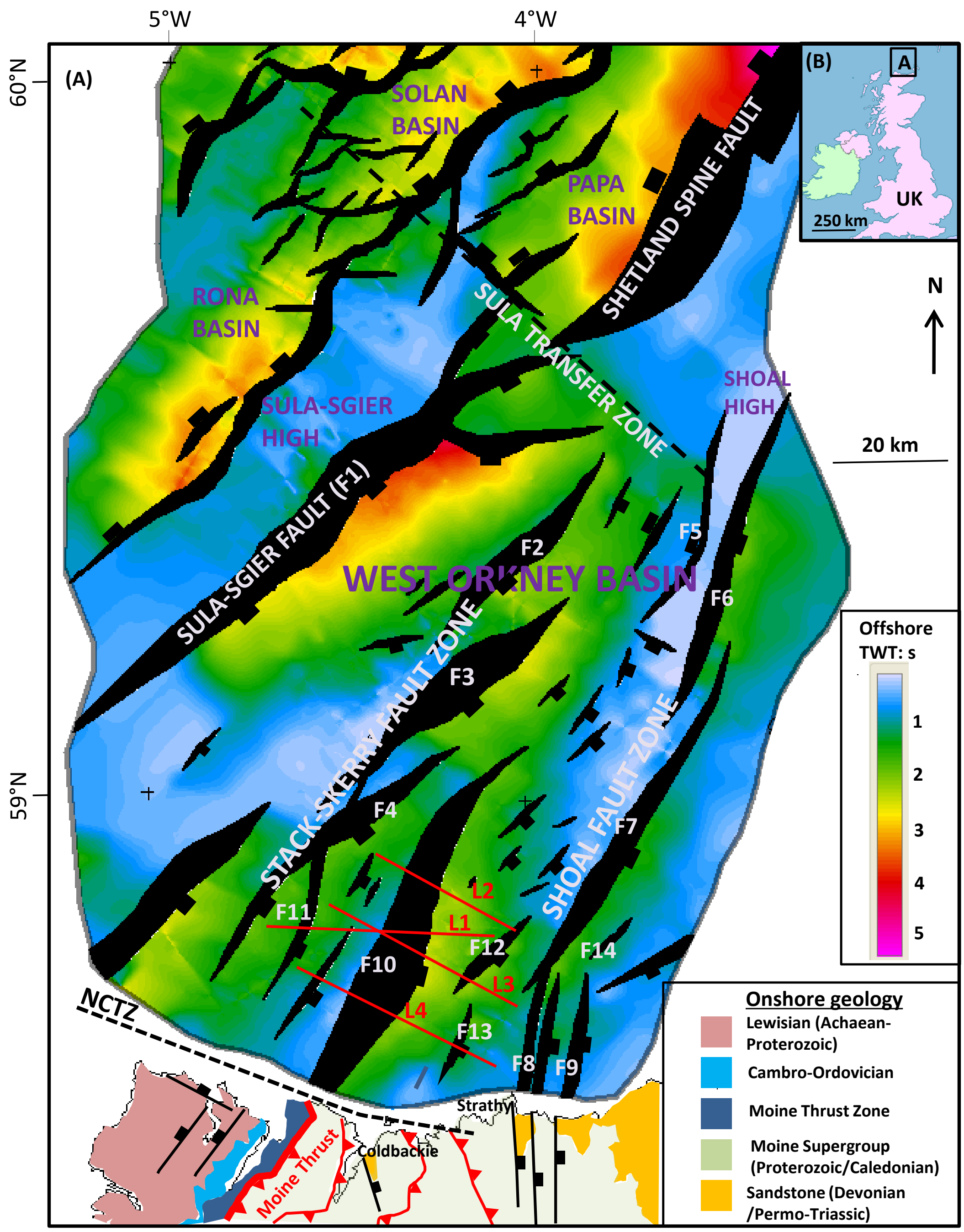


Figure 3-1. Structural interpretation of the top-basement in the West Orkney Basin (WOB) and surrounding basins. Interpretation is based on 2D seismic mapping during this study. The relatively high density of relay zones evident in the WOB, are proposed to be the result of the rift-system forming a partially exploitive relationship with basement fabrics, where extension has been accommodated between segments that have reactivated basement fabrics and segments that have not. Faults discussed in text are numbered F1 to F13. Locations of seismic lines in figures 3.4 to 3.7 are also illustrated. Onshore geology is simplified from Wilson et al. (2010). Abbreviations - NCTZ: North Coast Transfer Zone.

interpretation is equivocal, due to extensive Palaeozoic and Mesozoic rift events that formed the WOB (e.g. Wilson et al. 2010), and thus, it is not clear how these later rift structures are portrayed throughout the crust on seismic, and even if offshore structure can be simply correlated with the onshore geology.

Coward (1988) proposed that the north of Scotland may have been situated over a major lateral structure during the Caledonian, that acted to separate a detachment dominated regime (onshore) from whole crustal imbrication (offshore). Alternatively, Butler and Coward (1984) suggested that steeply dipping seismic reflection events imaged offshore could be structure within the foot-wall to the Moine Thrust Belt and therefore their relationship to shallowly dipping Caledonian structures onshore is unknown.

Nonetheless, some studies have advocated a basement reactivation theory for formation of the West Orkney Basin (WOB); based on the observation that extensional faults in the West Orkney Basin (WOB) trend parallel and are directly correlatable with specific intra-basement seismic reflections (Brewer & Smythe 1984; Enfield & Coward 1987; Snyder 1990; Wilson et al. 2010). This theory has been questioned due to the lack of evidence for reactivation of basement fabrics along the north coast of Scotland (e.g. Holdsworth et al. 2001), where it can be observed that rift-related faults cut both pre-existing Pre-Cambrian (situated to the west of the Moine Thrust Zone) and Caledonian fabrics at high angles (Wilson et al. 2010).

The main focus of this paper is to describe the intra-basement reflectivity and the structural relationships between domains of systematic intra-basement reflection configurations and the major rift structures of the WOB, in order to test ideas about basement reactivation during rifting (e.g. Brewer & Smythe 1984; Enfield & Coward

1987; Snyder 1990; Wilson et al. 2010). The rift history of this basin is complex and polyphase, and beyond the scope of this paper to interpret and describe in detail, and is the subject of current research efforts in this area.

This study uses a denser 2D seismic grid than was available to previous studies (e.g. Enfield & Coward 1987; Snyder 1990). This new data compilation includes a number of profiles that have been recently reprocessed with modern noise reduction algorithms. The better definition of both basement reflectivity and rift-fault geometry that results from the new data compilation, provides a more tightly constrained basis and allows a secondary aim of evaluating previous structural models linking the onshore and offshore regions of this classic area of regional structural geology.

3.2 Regional Geology

3.2.1 West Orkney Basin:

In general, the WOB consists as a series of south-eastward-dipping half-grabens (Fig 3.1). Only two exploration wells have been drilled in the east of the basin (locations illustrated on Fig 3.2), which encountered an entirely Permo-Triassic succession, over 3 km thick (Hitchen et al. 1995). The wells reached their total drilled depths (TD) considerably above the top of the seismically interpreted basement and therefore the presence of a Devonian succession in the basin is poorly constrained and largely unknown.

Sedimentary outliers of Devonian to Permo-Triassic rocks unconformably overlie Moine basement at Strathy and Coldbackie along the north coast of mainland UK (Fig 3.1). Paleontological evidence favours a Devonian age for the outlier at Strathy (Donovan 1975). The age of the outlier at Coldbackie is more difficult to determine due to the lack of fossil assemblages. However, sedimentological evidence favours a Devonian age for the lower portion of the outcrop and Permo-Triassic for the upper section (Wilson et al. 2010).

Wilson et al. (2010) carried out detailed outcrop analysis of the post-Caledonian extensional patterns associated with these outliers and provided strong evidence for fault systems consistent with NW-SE extension, that post-date an interpreted ENE-WNW (Devonian) extensional fault array. The later phase of extension appears to have included the development of a coast parallel transfer fault system (NCTZ) and the location of this is illustrated on figure 3.1. Additionally, these authors evaluated offshore seismic in the WOB, and argued that it is also possible to split the offshore stratigraphy into two phases of fault movement, and therefore together with the onshore evidence, proposed a two-phase rift model for formation of the WOB (Devonian and Permo-Triassic).

However, there is a considerable lack of understanding on the distribution and magnitude of these rift events across the basin, mainly because the lack of well control, and is subject to current research. Furthermore, the WOB has been extensively exhumed with removal of perhaps 2 – 3 km of section (e.g. Holford et al. 2010), and thus it is possible that a portion of the extensional faults in the WOB could post-date the preserved sequences altogether.

3.2.2 Basement geology:

The collision between Baltica and Laurentia during the Scandian (Silurian) phase of the Caledonian orogeny is expressed in the Northern Scottish Highlands (Fig 3.1) as a WNW-vergent fold-and-thrust belt (The Moine Thrust Belt) (Leslie et al. 2010 and references therein). The Moine Thrust Zone defines the boundary between the pervasively deformed Caledonian orogenic belt to the east and a foreland of continental crust to the west. The foreland consists of mainly Late Archean to Proterozoic amphibolites-facies gneisses (Lewisian Complex) that is unconformably overlain by a Torridonian sequence of sandstones and conglomerates and a shelf sequence of Cambro-Ordovician quartzites and dolomitic shales (Butler & Coward 1984). The foreland is largely absent from the effects of Caledonian deformation. However, the Lewisian Complex possesses a well-developed, steeply-dipping WNW-ESE striking fabric of Paleoproterozoic age (Wilson et al. 2010). Greenschist to amphibolite-facies meta-sedimentary rocks of the Neoproterozoic Moine Supergroup lie in the hanging wall, and to the east of the Moine Thrust (Winchester 1974; Fettes et al. 1985; Streule et al. 2010). These rocks were deformed in the middle crust, by ductile thrusting and folding, and are particularly interesting because thin thrust sheets of the Lewisian Complex have been incorporated into the thrust belt. The Moine Nappe is characterised with a strong Caledonian foliation, with a dominant strike of NNE-SSW. However, there a few localised regions where the strike differs slightly, due to later ductile deformation events (Wilson et al. 2010).

3.3 Dataset and methodology

The relationship between basement structure and rift architecture of the WOB was analysed on a 2D seismic dataset (Fig 3.2) consisting of three deep seismic profiles (from Snyder & Hobbs 2000) immediately off the north coast of Scotland and four different commercial seismic surveys (acquired in the 1980s and 1990s) that cover the

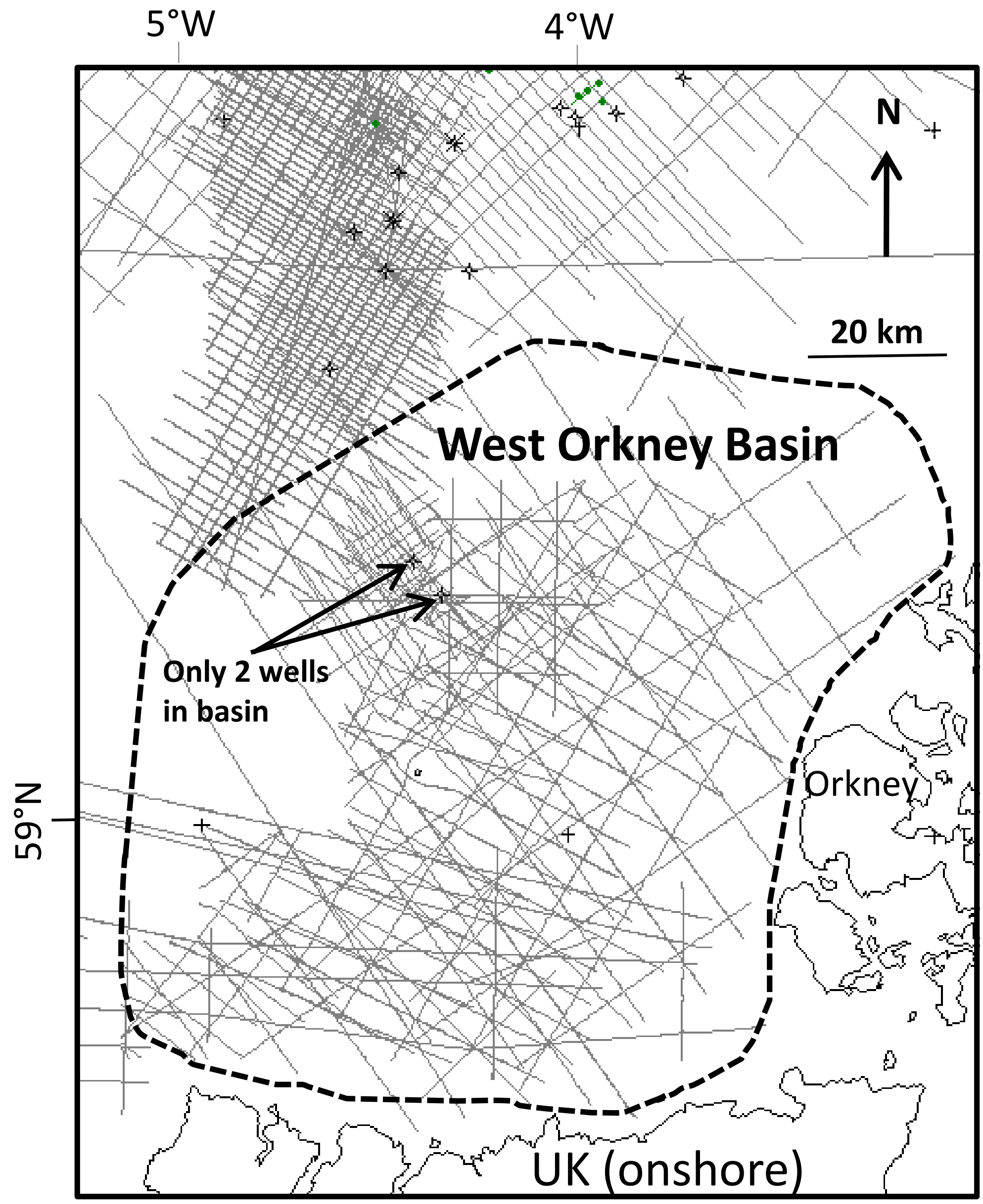


Figure 3-2. 2D seismic dataset used in this study; comprising three deep seismic profiles (from Snyder & Hobbs 2000) immediately off the north coast of Scotland and four different commercial seismic surveys (acquired in the 1980s and 1990s) that cover the entire basin. The total line kilometre length of the profiles available to this study in the WOB was about 10000 km, giving an average line spacing of 5 km in the WOB. Industry reprocessing of a total of 579 km line length of the commercial seismic profiles was carried out in 2012

entire basin. The total line kilometre length of the profiles available to this study was about 10000 km in the WOB, giving an average line spacing of 5 km.

Industry reprocessing of a total of 579 km line length of the commercial seismic profiles was carried out in 2012 and the results were made available for this study. The objective of the reprocessing was to improve definition and continuity of intra-Devonian reflections within the fill of the half-grabens, rather than specifically aiming at improving intra-basement definition. But this led to better definition of extensional faults bounding half-grabens and of the top basement surface.

One advantage of having four separate commercial surveys available in the combined dataset of this study is that it facilitated the recognition of acquisition and processing artefacts. In addition, large variation in acquisition and processing techniques between the different surveys allowed for the interpretation and lateral continuity of intra-basement reflections to be rigorously tested, since velocity models and stacking/migration algorithms were unique to each survey. By comparing intra-basement imaging on closely adjacent lines, it was possible to build confidence in the continuity of these reflections as they were correlated through the grid. The positions of extensional faults in the basin were interpreted by picking systematic alignments of stratal cut-offs and fault plane reflections.

Depth conversion of three commercial seismic lines was carried out to validate and quantify geometric interpretations made on time seismic sections. There is only velocity information (check-shot survey) for the Upper Permian to Triassic rocks within the two exploration wells in the east of the basin (Fig 3.2), and as their distribution is poorly constrained elsewhere in the basin, a constant interval velocity of 4300 ms^{-1} was used for the complete sedimentary section. A constant interval velocity of 6200 ms^{-1} was assumed for basement, and is based on velocity analysis during reprocessing of the data.

3.4 Rift architecture of the West Orkney Basin

Previous published mapping (e.g. Fig 1.3) of the WOB defined the rift architecture of the basin to take the form of a simple fault system of long, interleaving curvilinear fault traces (Enfield & Coward 1987). With the closer spaced grid of this survey (Fig 3.2), the major faults mapped at top-basement level can be seen to follow more linear trajectories, but with shorter lengths, organised into more complex, segmented fault arrays, that are soft or hard-linked at relay zones (Fig 3.1). The major faults within the basin generally strike NNE to NE and dip towards the south-east, which is the opposite structural polarity to the major sedimentary basins to the immediate northwest of the WOB (Fig 3.1: Rona, Papa, Solan Basins).

The structural expression of the top of the basement reflects the geometry of post-Caledonide rifting (Fig. 3.1). Generally, there is not a strong top-basement seismic reflection event that can be mapped within the basin, due to the subtle velocity contrasts between sediments in the bottom of the half-grabens and basement. Nonetheless, its position in the basin is very well defined; because in the eastern half of the basin, it appears as a mappable angular unconformity between west-dipping reflections from sediments (presumed Devonian to Permo-Triassic age) within the half-grabens and strong east-dipping (probable Caledonian age) intra-basement reflections. In the west of the basin (west of the Stack-Skerry Fault Zone), intra-basement reflectivity is less obvious, with the basement appearing almost opaque in acoustic character below well stratified west dipping stratigraphy within the half-grabens.

3.4.1 Description of major faults in map view:

The Sula-Sgier Fault (F1) bounds the basin to the west with a maximum top basement throw of 3.7s TWT (8 km) and fault length of 110 km (Fig 3.1). At its northern tip, it splays into three smaller fault segments and forms a major conjugate transfer zone (sensu Morley et al. 1990) with the west dipping Shetland Spine Fault. The location of this major change in half-graben polarity also coincides with the juxtoposition of the Papa Basin against the basement-cored Sula-Sgier high by a NW-SE trending fault. This provides evidence for the possible existence of a NW-SE transfer zone, that we name here the 'Sula Transfer Zone' (Fig 3.1). The Sula Transfer Zone may be related to other NW-SE orientated transfer zones on the margin (e.g. Moy & Imber (2009): Clair and Judd Transfer Zones). The projected northwest strike of the transfer zone correlates with the southern margin to the Solan Basin, and by interpolation to the SE, it coincides with the northern boundary to the WOB. Therefore, the Sula Transfer Zone may have played a significant role in both accommodating rift polarity changes and subsidence within this area of the margin, since at least Permo-Triassic times.

Within the central sector of the basin, Faults: 2, 3 and 4 form a 85 km en-echelon, left stepping fault array (Stack-Skerry Fault Zone), with maximum throw of 1.7s TWT (3.7 km) on Fault 3. The average line spacing across the regions of fault overlap is 2 to 3 km (Fig 3.2), thus allowing for the geometry of the two relay zones to be resolved. Faults 3 and 4 are breached across the relay ramp by a more northerly striking fault, whereas the relay ramp between Faults 2 and 3 is not breached at the seismic scale of resolution.

In the north-east of the basin (Fig. 3.1), Faults 5 and 6 form a basement horst (Shoal High). Both faults have a more northerly strike than the faults within the middle of the basin. Fault 5 loses displacement towards the south, resulting in the horst changing laterally into a footwall high, that is bounded by the left-stepping, en-echelon fault network of Faults 6, 7 and 8 (Shoal Fault Zone), which combine to form a structure 130 km in length. The relay ramps formed at the fault overlaps are not breached at the seismic scale (dip line spacing between Fault 6 and Fault 7 overlap is 9.5 km, and 6 km between Fault 7 and Fault 8 overlap). Faults 6 and 7 have the largest top basement throws within the east of the basin: 1s TWT (2.2 km) and 1.4s TWT (3 km) respectively.

In the southern extremities of the WOB, maximum throw at the level of the Top Basement occurs on Fault 10 (1.9s TWT / 4.1 km). The projected throw gradient from the offshore seismic dataset to the onshore indicates that the fault has an inferred top-basement fault heave of about 4 km, within 2 km of the onshore, and therefore it cannot simply strike onshore to correlate with any of the onshore faults (Fig 3.1). This gives strong evidence that a portion of the displacement on Fault 10 is Permo-Triassic in age, where displacement has been accommodated onshore by the North Coast Transfer Zone (e.g. Wilson et al. 2010).

In contrast, the onshore continuation of the Shoal Fault Zone (e.g. F8 and F9) is less questionable, since it appears to simply link with north-south trending faults onshore. Although with different interpreted offshore structural maps, previous studies have also shown a simple onshore-offshore correlation at this location in the basin (e.g. Enfield & Coward 1987; Coward et al. 1989).

3.5 Intra-basement structure and its relationship to rift architecture

A crustal scale boundary in acoustic character of the crystalline basement (referred to as Horizon MT) and three overlying intra-basement reflection packages (Packages: A, B and C) were recognised on seismic in the WOB (Figs 3.3 – 3.7), and are described below. The criteria for simplifying and subdividing basement reflections into three mappable packages (A, B and C), are based primarily on reflection dip, but also their seismic character and geometric relationship to overlying normal faults in the WOB. The along strike structural variation in Packages A, B, and C, and their association with extensional faulting in the WOB, is exemplified on both a deep crustal seismic line from BIRPS (Line 1: Fig 3.4) and three commercial seismic lines (Lines 2 to 4: dip line spacing of 5 km) in figures 3.5 to 3.7. The results from depth converting Lines 3 (Fig 3.6) and 4 (Fig 3.7) are illustrated in figure 3.8.

3.5.1 Horizon MT:

Horizon MT is expressed as a regionally mappable acoustic boundary between two distinct basement units; an upper unit consisting of locally mappable packages of strong reflections and a lower unit containing no coherent or laterally continuous reflections, comprising instead chaotic and discontinuous reflections interpreted to be largely noise (Figs 3.4 to 3.7). Horizon MT can be traced with considerable

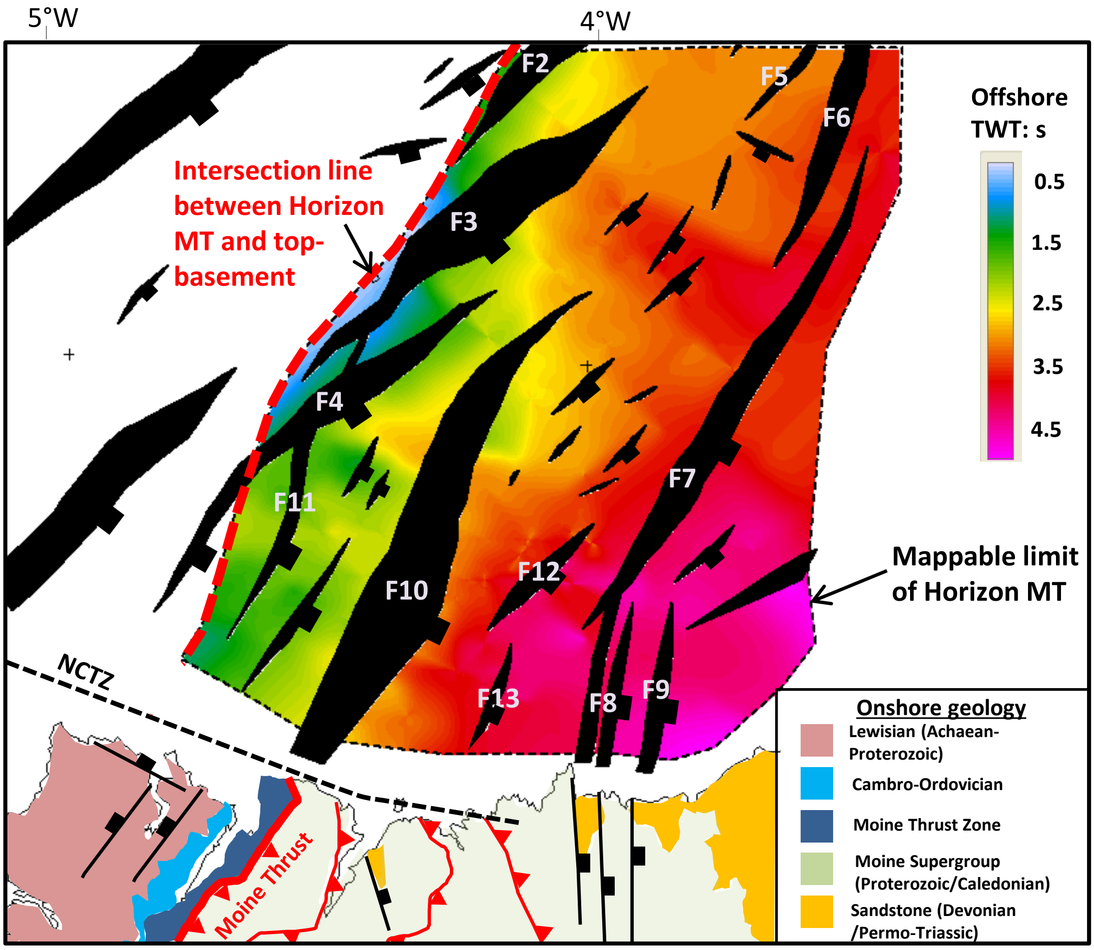


Figure 3-3. Structural map (TWTs) of Horizon MT - interpreted to represent the offshore equivalent to the Moine Thrust. The position of top-basement footwall and hanging-wall cut-offs from the top basement structural map in Fig 1 are also illustrated. Note: the half-grabens of the WOB mainly strike oblique to Horizon MT. Onshore geology is simplified from Wilson et al. (2010).

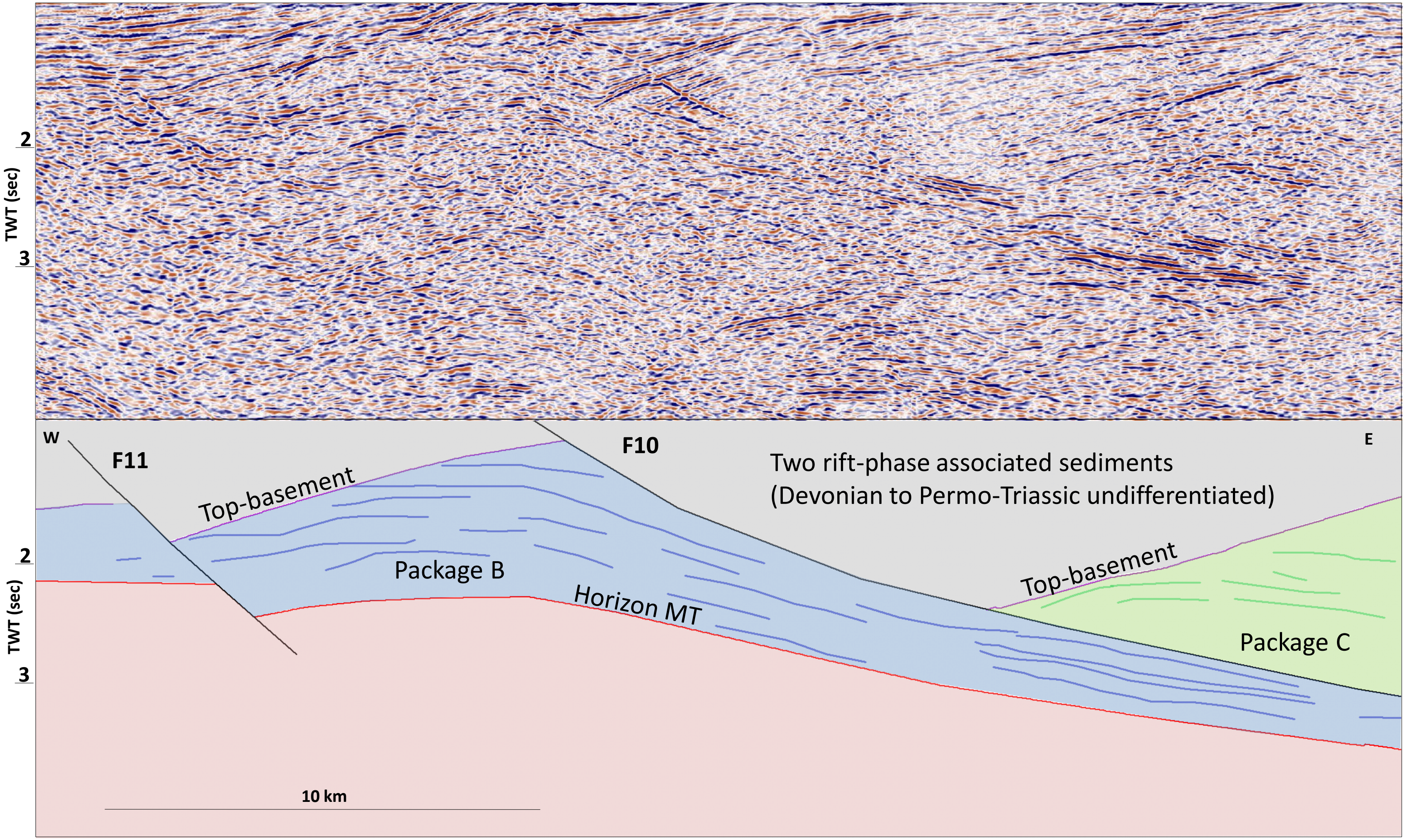


Figure 3-4. Line 1. This studies re-interpretation of deep seismic profile DRUM from Snyder & Hobbs (2000). Note that Fault 11 cross-cuts basement fabrics. Location of line shown in Fig. 3.1

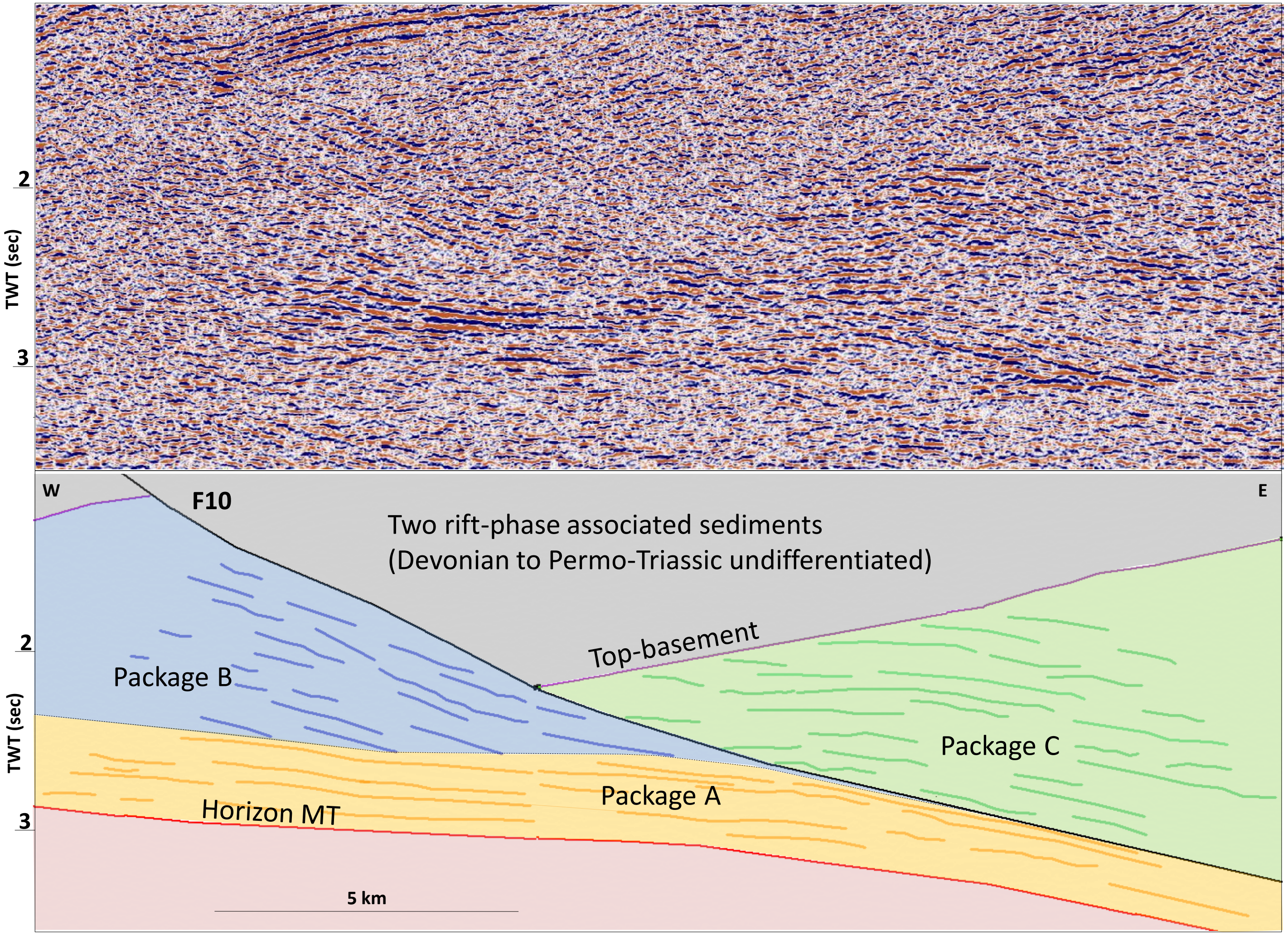


Figure 3-5. Line 2. Note the apparent dip discordance between reflections in Package A and Package B. Location of line shown in Fig. 3.1.

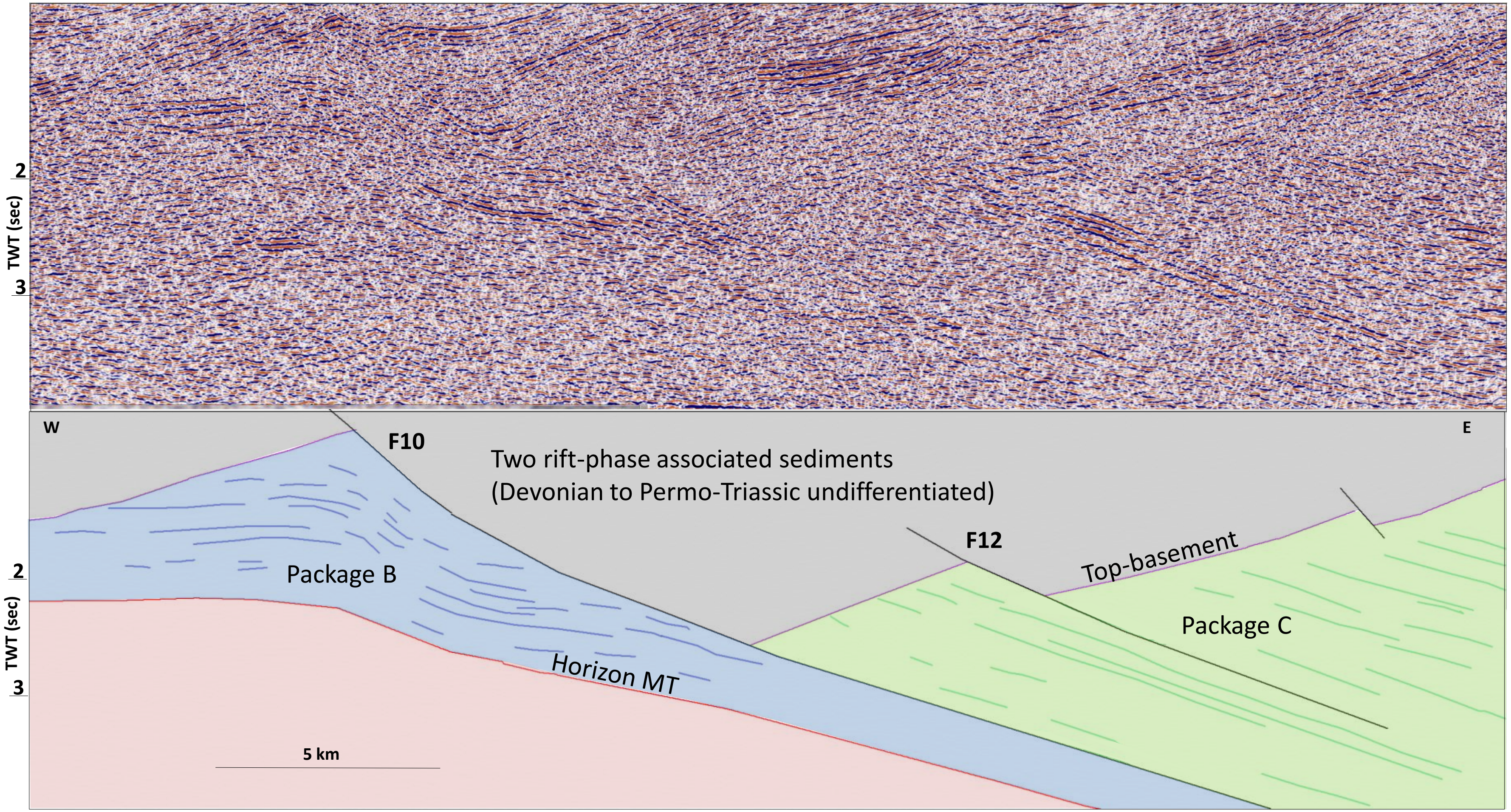


Figure 3-6. Line 3. Location of line shown in Fig. 3.1

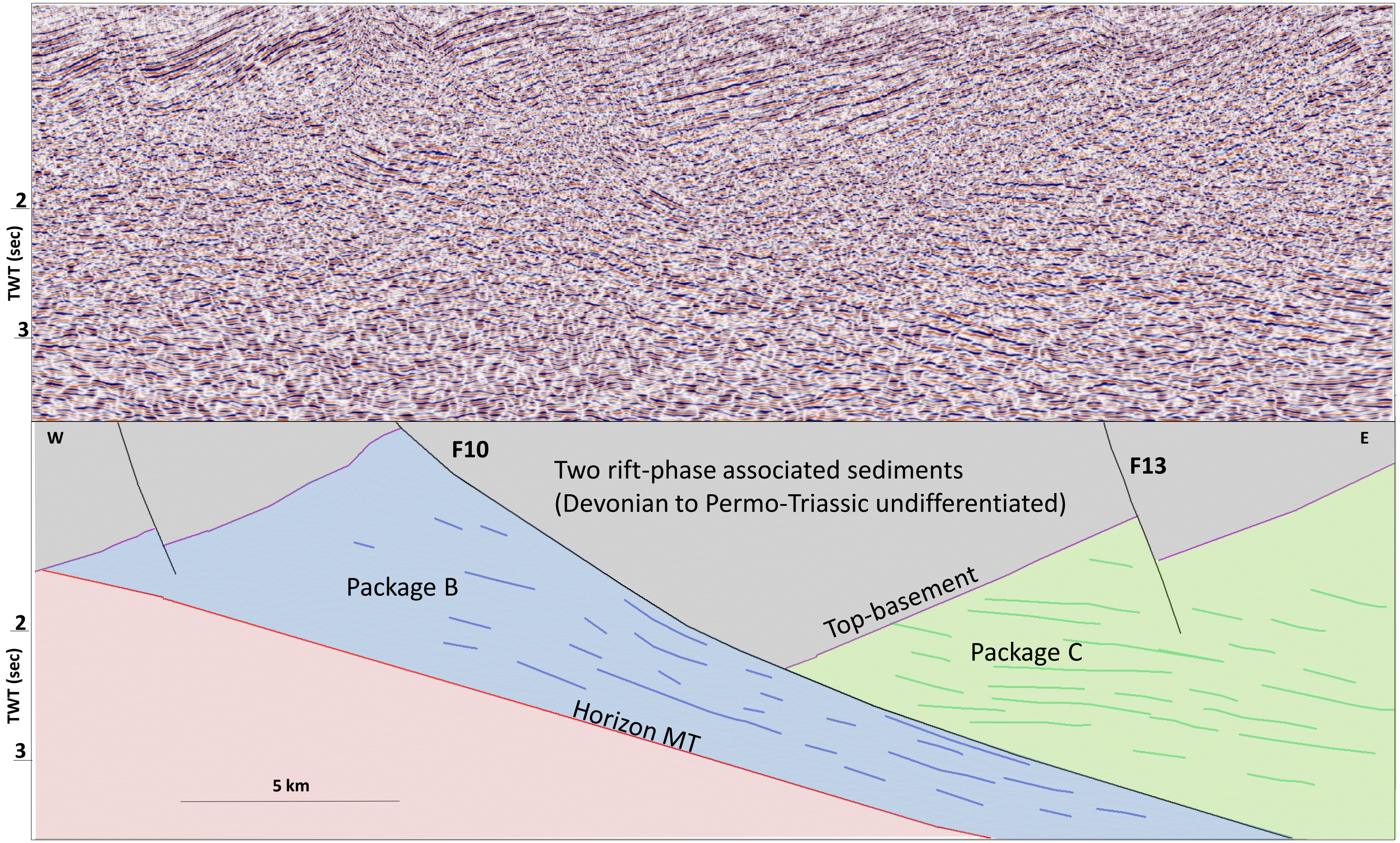


Figure 3-7. Line 4. Location of line shown in Figs. 3.1.

confidence over a large area (>60%) of the basin (Fig 3.3), with good ties between dip and strike lines throughout this area. The boundary is equally recognisable on profiles that have been reprocessed recently (e.g. Fig 3.7), and those that have not (e.g. Fig 3.4 and 5).

A structural map of Horizon MT (Fig 3.3) indicates that this boundary is irregular in geometry, with a varying dip of 0 to 25º to the south-southeast. Generally at depth, it flattens out to near horizontal at 4 to 4.5s TWT in the south and 3 to 3.5s TWT in the north of the WOB. The positions of footwall and hanging-wall cut-offs at top-basement level for the half-grabens in the basin are also illustrated on the structural map in figure 3.3; which demonstrates that the strike of Horizon MT is oblique to the majority of overlying normal faults.

A critical observation made is that the extensional faults that overly Horizon MT clearly detach onto or close to Horizon MT (Figs 3.4 to 3.7), whereas fault blocks to the west are less rotated and are interpreted to sole out at deeper depths into the lower crust. However, there are some local exceptions to this relationship, for example a fault plane reflection from Fault 11 on seismic line 1 (Fig 3.4) can be interpreted to offset gently dipping reflections within Package B and Horizon MT. These local exceptions appear to correspond to regions where Horizon MT is characterised by shallower dips.

3.5.2 Package A

Package A is locally defined in the central part of the basin as a 1200 to 1400 m thick set of moderate to high amplitude, continuous to weakly discontinuous reflections, which are bounded at their base by Horizon MT (Fig 3.5). Package A can only be mapped as a distinct coherent package of reflections in areas where its upper boundary is discordant with overlying reflections, as exemplified on seismic line 2 (Fig 3.5).

3.5.3 Package B:

On seismic line 1 (Fig 3.4), the reflections within Package B are relatively high amplitude, continuous and discordant with reflections in Package C. On this profile, the upper boundary to Package B is Fault 10, whose position is well constrained from a strong fault plane reflection. The reflections within Package B are discordant in dip with the fault plane reflection above 2s TWT and concordant with it below 2s TWT. On line 3 (Fig 3.6), the reflections are similar in character to those imaged on line 1 (Fig 3.4), where they appear folded and discordant (relationship supported on depth section: Fig 3.8) with Fault 10 above 2.5s TWT and concordant below. Whereas, further north on line 2 (Fig 3.5), the dip of the reflections steepens (to about 35°), becoming parallel or near parallel to Fault 10. In the south on line 4 (Fig 3.7), the reflections are relatively discontinuous and concordant with Fault 10 (30° – 35° dip: Fig 3.8).

3.5.4 Package C:

Package C comprises the basement reflections seen in the hanging-wall block of Fault 10 (Figs 3.4 to 3.7). Generally, the reflections within the package are aligned and straight. On seismic line 4 (Fig 3.7), the dip projection of Fault 10 into basement corresponds exactly with the lower boundary to Package C and the reflections within

Package C (dipping at about 5° dip) are clearly discordant with this boundary, on both time and depth sections (Figs 3.7 and 3.8). Fault 13 on line 4 (Fig 3.7) has a relatively steep dip of 60°, and it most likely projects into basement cross-cutting reflections within Package C. Similarly, further to the north on line 2, the reflections within Package C are shallowly dipping (Fig 3.5). Whereas, on seismic line 3 (Fig 3.6), they are parallel to Fault 10, with about a 20° dip.

3.5.5 Interpretation of intra-basement structure

Horizon MT defines a major acoustic boundary in basement reflectivity. The highly reflective Packages A, B and C contain laterally continuous reflections that show high degrees of internal concordance (within the confines of each designated Package), with thicknesses of up to about 10 km for individual packages. Possible interpretations of these packages could include thick shear zones comprising mylonitic complexes, or metasedimentary units. The latter seems more likely, given the internal continuity and concordance. If these packages are indeed metasedimentary, then it seems most likely that they represent elements of the Moine Supergroup, with a possible minor contribution from sedimentary (Cambro-Ordovician) units. The absence of coherent basement reflections beneath Horizon MT equally accords well with an interpretation of this unit as Lewisian foreland, given the likely gneissic composition of the Lewisian in this area (e.g. Mendum et al. 2008). The evidence for reflections within Packages B and C detaching into or close to Horizon MT (e.g. Fig 3.5) leads us to suggest that Horizon MT probably represents a basal detachment zone to overlying Caledonian crust, and thus, it is interpreted to represent the offshore equivalent to the Moine Thrust.

Further insight as to the nature of intra-basement reflectivity in this area (e.g. thrusts, shear zones, meta-sedimentary layering) above Horizon MT can be gained, by considering that Devonian to Permo-Triassic rocks of the West Orkney Basin unconformably lie upon on a mid-crustal Caledonide thrust system. This juxtaposition implies that perhaps 20-30 km of upper crustal rocks have been peneplaned prior to initiation of the West Orkney Basin (e.g. Winchester 1974; Fettes et al. 1985; Watson 1985; Streule et al 2010). Thus, the top the top-basement on the depth sections in figure 3.8 can be restored to horizontal by back rotating the extensional fault blocks to yield the geometry of basement reflections (i.e their exposure angle at the surface) prior to post-Caledonide extension.

Restoring Packages A, B and C (Fig 3.8) results in a steepening of dip, and the dip discordance between the packages is most plausibly explained by interpreting the position of thrusts at the package boundaries. The apparent along strike variation in dip of Package C across the seismic lines described in this study is therefore interpreted to be the expression of doming of a Moine Nappe in the hanging-wall to a major thrust.

The interpretation of a detachment-dominated thrust system in figure 3.8 is compatible with the model of Butler and Coward (1984) for the onshore crustal structure of NW Scotland. If Horizon MT does indeed represent the offshore equivalent to the Moine Thrust, then the structural map of Horizon MT (Fig 3.3) shows it to sole out within the crust below the West Orkney Basin at about 4 to 4.5s TWT (~9.5 to 13 km) in the south and 3 to 3.5s TWT (~7 to 10.5 km) in the north, which is much greater than the 5 km depth suggested for the onshore model of Butler and Coward (1984). This apparent differential depth of detachment between onshore (e.g. Butler and Coward 1984) and offshore (Fig 3.3), could be explained by northern

Scotland being positioned over an inferred major lateral structure during the Caledonian (e.g. Coward 1988). However, we propose the variation in depth to detachment can be more easily explained from the knowledge that the offshore has experienced considerably greater subsidence (~5 to 10 km) than onshore, and therefore Caledonide basement structures would be expected to be currently positioned at greater depths within the crust, than is the case onshore.

3.6 Discussion

This new analysis of the West Orkney basin has demonstrated that the rift architecture of the WOB is generally more linear with a prominence of relay zones relative to previous interpretations (e.g. Enfield & Coward 1987), and that rift structures form complex discordant and concordant relationships with pre-rift Caledonide basement structures.

Normal faulting overlying Horizon MT visibly detaches into or close to Horizon MT (Figs 3.4 to 3.7), suggesting that the interpreted offshore continuation of the Moine Thrust may have been reactivated as a low angle extensional detachment during rifting (Fig 3.8). However, it appears that only partial reactivation has occurred, because in regions where Horizon MT is characterised by a low dips, overlying faults cross-cut Horizon MT (e.g. Fig 3.4: Fault 11). We propose that these localised regions of non-reactivation are energetically unfavourable for newly propagating extensional faults to reactivate the thrust zone.

Restoration of basement fabrics to their pre-extensional geometry indicates that the reactivation of basement structures as normal faults appears to have only occurred where the pre-extensional-dip of basement structures is greater than 30° (Fig 3.8).

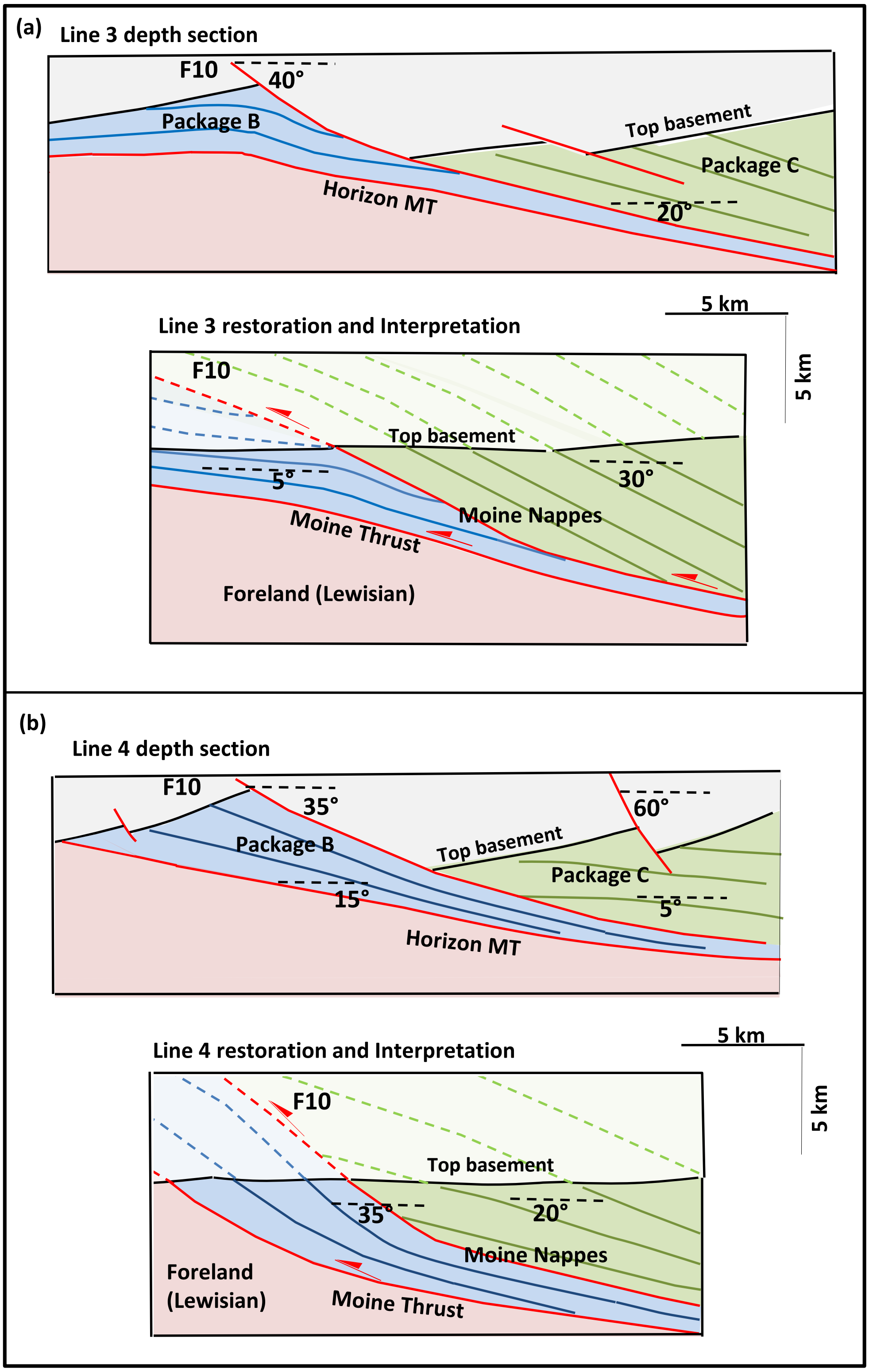


Figure 3-8. Depth converted sections of seismic lines 3 and 4 (illustrated in Figs: 3.6 and 3.7) and structural restoration of top-basement to horizontal, with corresponding basement structure interpretation. Extensional reactivation with formation of normal faults appears to have only occurred where the pre-extensional dip of basement fabrics is greater than 30º. The positions of thrusts are interpreted to explain the discordance in dip between reflection packages.

Thus, this study suggests that the pre-extensional dip of basement fabrics has been a major controlling factor in controlling whether pre-existing structures reactivate or not.

Additionally, the structural configuration of the basement has exerted a considerable control on the rift architecture of the West Orkney Basin. The extensional fault with the largest throw in the south of the basin (Fault 10) has not only formed where the dip of pre-existing fabrics favour it, but also at the site of an interpreted thrust.

A synthesis of onshore structural studies (e.g. Wilson et al. 2010) with the results from this study, leads us to suggest that the rift structures formed a partially exploitive relationship with basement fabrics, where during extension there were likely both newly forming fault surfaces as well as reactivated ones. We propose the relatively high density of transfer zones along the length of the Stack-Skerry Fault Zone (Fig 3.1) are the result of the rift system accommodating extension between segments that have or have not reactivated basement fabrics.

The evidence of partial basement reactivation documented in this paper is based principally on the relationships observed between the position of basement extensional faults and the intra-basement reflectivity. This approach does not allow us to specifically address the interesting question of how the reactivation may have been partitioned in time between the two separate rift phases interpreted for this basin by Wilson et al (2010), since this would require a quantitative analysis of the displacements that accrued in each of these two phases. Understanding this partitioning of reactivation between two distinct phases separated by a long period of dormancy of the major basement faults is a major goal of current research in this study area.

3.7 Conclusion

1. Our new structural mapping of the west Orkney basin has redefined the rift architecture of the basin; from earlier concepts of a simple fault system of long-interleaving curvilinear fault traces (e.g. Enfield and Coward, 1987), to a more complex segmented fault system.
2. A major detachment zone in intra-basement reflectivity was identified between two different crustal basement terranes and is interpreted to be the offshore equivalent to the Moine Thrust.
3. The major component of basement reflectivity most likely represents sedimentary (Cambro–Ordovician) and meta-sedimentary rock (Moine Supergroup) layering, and not individual thrusts and shear zones. The positions of thrusts are interpreted to explain the discordance in dip between reflection packages.
4. Post-Caledonian crustal extension appears to have been accommodated at different detachments levels within the crust. We propose that the normal faults in the east of the basin strike oblique to and partially reactivate the offshore equivalent to the Moine Thrust (Horizon MT) as a low angle extensional detachment, whereas in the west fault blocks are less rotated and sole out at deeper depths into the lower crust.
5. The relationship between post-Caledonian extensional faulting and packages of basement reflections varies from concordant (reactivating) to discordant (cross cutting). The geometry of Caledonian structure prior to post-Caledonian extension has been revealed by back rotating the extensional fault blocks. Reactivation of basement fabrics with formation of normal faulting has occurred where the pre-extensional dip of basement fabrics is greater than 30º.
6. The structural configuration of basement structure has had a significant control on the rift architecture of the West Orkney Basin, where it has influenced fault dip, position of extension, and segmentation of the rift system.

Chapter 4

4 Tectono-stratigraphic Evolution of the West Orkney Basin

4.1 Introduction

Previous published structural mapping of the WOB (e.g. Enfield & Coward 1987) defined the rift architecture of the basin to take the form of a simple fault system of long, interleaving curvilinear fault traces (Chapter 1: Fig 1.3). In the preceding chapter (Chapter 3), the basement structure and rift architecture of the WOB was entirely redefined from these earlier studies; to show the WOB to comprise a more complex, segmented fault array (e.g. Fig 3.1). This new structural interpretation is used in this chapter as a structural framework for basin analysis.

Devonian rocks, including Devonian source-rocks, outcrop on the Orkney Islands and along the NE coast of Mainland UK. However, a Devonian succession has not been penetrated by wells in the offshore portion of the WOB. Earlier studies have suggested that Devonian strata may be present in the east of the WOB (Earle et al. 1989, Stocker et al. 1993; Wilson et al. 2010). This interpretation is based only on an inferred structural continuity between Devonian outcrops onshore and half-grabens interpreted on seismic profiles located immediately offshore.

Due to the lack of preservation of rocks younger than Triassic in the WOB, the understanding of the post-Triassic evolution/burial and uplift history of the WOB is not straightforward, and consequently, a considerable portion of the faulting observed on seismic data within the basin could post-date deposition of the preserved (Devonian? to Permo-Triassic) sequences.

The amount of eroded section across the WOB has been estimated to be 1.85 km by comparing sonic and density data from Triassic mudstones in WOB exploration well 202/19-1 with published shale velocity-depth curves (Evans 1997). More recently, Holford et al. (2010) carried out apatite fission-track analysis (AFTA) on Permo-

Triassic rocks encountered in well 202/19-1 and shallow BGS boreholes, and proposed that up to 2-3 km of Upper Triassic to Lower Cretaceous rocks may have been deposited in the basin prior to Early Cretaceous exhumation.

In this chapter, a comprehensive structural-stratigraphic seismic analysis is carried out on the WOB seismic dataset. Tectono-stratigraphic sequences are defined and discussed in the context of tectono-stratigraphic development of the WOB.

The post-Triassic evolution of the WOB is evaluated and modelled, by conducting extensive seismic mapping in the basins to the immediate northwest of the WOB (Rona, Solan and Papa Basins), where there are Mesozoic and Tertiary sediments preserved. This new work is discussed and synthesized with the results from seismic mapping in the WOB and with published AFTA (e.g. Holford et al. 2010), in order to construct a new tectono-stratigraphic evolutionary model for the WOB.

4.2 Tectono-stratigraphic Evolution of the WOB

The major fault zones interpreted in the WOB in chapter 3 are used here to subdivide the WOB into three sub-basins for basin analysis (Fig 4.1): where the Shoal and Stack-Skerry Faults Zones are the western boundaries to the Shoal and Stack-Skerry sub-basins respectively, and in the west, the Sula-Sgier Fault is the western limit to the Sula-Sgier sub-basin.

Past studies (Enfield and Coward 1987; Stocker et al. 1993; Wilson et al. 2010) of the WOB identified three sedimentary sequences (n.b. sequence here is used as an informal term denoting a seismically recognisable package of distinctive reflection character) bounded by three regional unconformities (Chapter 1: Fig 1.4). This study has distinguished five different tectono-stratigraphic seismic sequences within the basin (Fig 4.3), which are described below systematically from oldest to youngest.

4.2.1 Seismic analysis of the WOB

Two seismic reflection packages with contrasting seismic facies characteristics (Sequences 1 and 2) are discernible immediately above basement in the Shoal and Stack-Skerry sub-basins (Figs 4.3 to 4.9). Generally, Sequence 1 is composed of relatively weak amplitudes, whereas Sequence 2 contains more strong amplitude reflections. Both sequences are apparent on all seismic vintages within the WOB, which comprise different acquisition and processing parameters. For example, both sequences are visible on the shallow commercial seismic line (recently reprocessed) in figure 4.4, and the deep crustal seismic section from BIRPS in figure 4.7.

The seismic facies boundary between Sequences 1 and 2 can be confidently mapped with good ties on both strike and dip lines. A structural map of the boundary (Fig 4.10) reveals it to dip westwards at about 5° to 10°.

The lower boundary to Sequence 1 is very well defined, due to it being expressed as a mappable angular unconformity (Figs 4.3 to 4.9) between west-dipping reflections from within Sequence 1 and east-dipping intra-basement reflections, presumed to be Caledonian in age (nature of basement reflectivity discussed in Chapter 3).

An important observation made during this study is that the upper boundary to Sequence 2 is marked by an angular unconformity (Unconformity A). Reflections in sequences 1 and 2 appear truncated at the unconformity (Figs 4.3 to 4.9). The amount of eroded section at the unconformity does not appear to vary across the basin and is estimated to be about 300 to 1200 m from restoring the truncated reflections (Fig 4.9). A structural map of Unconformity A (Fig 4.11) shows it to dip westwards at about 10° in the Stack-Skerry sub-basin and truncates the seafloor in the Shoal sub-basin.

Reprocessing of selected seismic lines has led to a marked improvement in data quality and the stratal reflections. For example, on reprocessed seismic (e.g. Figs 4.4 to 4.6) the amplitude reflections within Sequence 1 appear parallel with moderate to high lateral continuity, whereas on the original processed version of the data, the reflections are discontinuous, giving the sequence an opaque appearance (e.g. Fig 4.9). In contrast, reflection continuity in Sequence 2 is moderate to high on both reprocessed (e.g. 4.4 to 4.6) and non-reprocessed seismic (4.7 to 4.9). There are no clear onlap relationships within either of these sequences.

Much of the apparent wedge shape of Sequence 2 appears to be due to erosion at Unconformity A. However, an important consideration in this interpretation is that the data available to properly evaluate divergence configurations of the seismic stratigraphy is limited: it is common that about only half of the original half-grabens are preserved (e.g. Fig 4.3).

Nonetheless, Sequence 1 does appear to thicken westwards below Sequence 2, and this cannot be attributed to erosion at Unconformity A. Therefore, it seems most probable that the Stack-Skerry and Shoal Fault Zones controlled deposition of Sequences 1 and 2, during the first stage of rifting in the basin.

The two isopach maps in figures 4.12 and 4.13 illustrate the preserved thickness and distribution of Sequences 1 and 2 (constant interval velocities of 5000 ms^{-1} and 4400 ms^{-1} were utilised respectively – seismic velocities discussed in Chapter 2) respectively. Within the Stack-Skerry sub-basin, both sequences are only preserved in the hanging-walls to Faults 2, 3 and 10 of the Stack-Skerry Fault Zone. They attain a maximum thickness of 2800 m (Sequence 1: Fig 4.12) and 2000 m (Sequence 2: Fig 4.13) in the hanging-wall of Fault 10. Whereas in the hangingwall to Fault 2, they are relatively thin (about 300 m for both sequences). Both sequences are present throughout the entire Shoal sub-basin with a maximum preserved thickness of 2300 m (Sequence 1: Fig 4.12) and 1500 m (Sequence 2: Fig 4.13) in the hangingwall to Fault 6 of the Shoal Fault Zone.

The isopach maps suggest that Faults 3 and 10 have dominantly controlled deposition in the Stack-Skerry sub-basin, whereas Fault 2 was relatively subdued. Within the Shoal sub-basin, the entire Shoal Fault Zone appears to have been active during deposition.

Sequences 1 and 2 are interpreted to not be present in the Sula-Sgier sub-basin. This is based on the lack of observation of their characteristic seismic facies and the identification of Unconformity A, which bounds the top of the sequences. The Sequences are interpreted to pinch-out to the north in the hangingwall of Fault 2 in the Stack-Skerry sub-basin. The continuation of Sequences 1 and 2 in the northern area of the Shoal Sub-basin is impossible to characterise due to the seismic being of extremely poor quality and full of multiples (e.g. Fig 4.14) in this region of the basin.

Immediately overlying Sequences 1 and 2 is a sequence with a remarkable distinctive geometry (Sequence 3) that thickens eastwards and downlaps onto Unconformity A (Figs 4.3, 4.15 and 4.16). The upper boundary to Sequence 3 is a well-defined onlap surface for Sequence 4.

Sequence 3 can be mapped throughout the WOB. It pinches out in the central to eastern area of the Sula-Sgier sub-basin and truncates at the sea floor in the east of

Stack-Skerry sub-basin (Figs 4.3, 4.15 and 4.16), where it attains a maximum preserved thickness of 1300 m (using an interval velocity of 4000 $ms^{-1)}$.

Reprocessing of seismic lines in this study has greatly improved resolution of Sequence 3. As a result, it is possible to sub-divide the sequence into two different seismic facies units (Figs 4.15 and 4.16) - Unit 1 and Unit 2. Unit 1 consists of relatively strong amplitudes that are moderately continuous, that truncate at the sea floor, resulting in a preserved lateral extent of about 15 km. Whereas, Unit 2 has a lateral extent of about 40 km and contains weaker amplitudes than Unit 1, which are moderate to highly continuous (amplitude continuity appears to decrease towards the west, as the sequence thins). The sub-division of Sequence 3 into Units 1 and 2 can be interpreted consistently on different vintages of reprocessed seismic, and therefore it most likely represents lithofacies variation within the sequence.

Sequence 4 onlaps onto Sequence 3 in the Stack-Skerry sub-basin (e.g. Figs 4.3, 4.15 and 4.16) and overlies basement in the Sula-Sgier sub-basin (e.g. Figs 4.3 and 4.17). The upper boundary to Sequence 4 is tied into the two exploration wells in the Sula-Sgier sub-basin (e.g. WOB 202/19-1 - Fig 4.3 and 4.18), where it is calibrated to the conformable boundary between Triassic and Upper Permian rocks (Fig 4.18). Although it should be noted that dating of the Permo-Triassic stratigraphy is poorly constrained (due to the lack of fossil assemblages) and should be treated with some caution, because it is based mainly on regional well-correlations of lithology and wire-line log response (Hitchen et al. 1995; Ritchie et al. 2011).

Exploration well 202/19-1 (Fig 4.18) was the deepest well drilled in the WOB and it only penetrated the upper section of Sequence 4 (Fig 4.3), in which a total of 1432 m of upper Permian rocks where encountered. Therefore, it is unknown if the entirety of

Sequence 4 is Permian or if the lower portion may be Devonian in age (discussed in detail in section 4.2.2).

Of the 1432 m of Upper Permian rocks encountered in well 202/19-1 (Fig 4.18), the upper 819 m consists of anhydritic mudstone and mudstone inter-bedded with thick beds of halite (up to 6 m thick) and thin beds of limestone, anhydrite and sandstone. The lower 613 m comprises sandy, anhydritic mudstone and claystone, with a few inter-bedded thin limestones (Hitchen et al. 1995).

The seismic facies of Sequence 4 generally comprises medium to strong and continuous reflections, whereas the lower two thirds comprise relatively less continuous reflections (e.g. Figs 4.15, 4.16, 4.17). This may indicate that only the upper portion of the sequence contains the evaporite-mudstone association.

The mapped position of the upper boundary (Top Permian) to Sequence 4 is relatively well constrained in the Sula-Sgier sub-basin, from seismic reflection correlation to the only two exploration wells to have been drilled in the basin (Fig 4.2 and 4.3). However, the position of the boundary in the Stack-Skerry sub-basin is more difficult to constrain, because it is problematic to map the boundary from the wells in the Sula-Sgier sub-basin, across the foot-wall high of the Stack-Skerry Fault zone, and into the Stack-Skerry sub-basin (e.g. Fig 4.1 to 4.3).

Nonetheless, a significant observation made is that some of the normal faults in the basin can be seen to detach into the upper part of Sequence 4, with associated roll-over folds, that overlie possible salt pillow structures, in both the Sula-Sgier (Fig 4.17, 4.19 and 4.20) and Stack-Skerry (Fig 4.21) sub-basins, which suggests evaporite-induced deformation (e.g. Jackson et al. 1996). Therefore, the location of detachment has been used to build confidence in interpreting the position of the top Permian (top Sequence 4) horizon in the Stack-Skerry sub-basin.

There is no evidence for any syn-sedimentary faulting being associated with deposition of Sequence 3. In contrast, the Stack-Skerry Fault Zone appears to have been extensionally reactivated, with the formation of new fault segments, during the deposition of Sequence 4. For example, Sequence 4 appears to thicken into both newly formed fault segments (e.g. Fault 4: Fig 4.22) and pre-existing faults (e.g. Fault 3: Figs 4.15 and 4.16) of the Stack-Skerry Fault Zone. Additionally, Sequence 4 can be seen to thicken into the Sula-Sgier Fault (Fig 4.17 and 4.20), where it reaches a maximum thickness in the basin (3000 m).

The Triassic sequence encountered in the two exploration wells (Fig 4.2 and 4.3 - wells: 202/19-1, 202/18-1) in the Sula-Sgier sub-basin consists of mainly fine grained sandstone with subordinate mudstone and calcareous siltstone (Fig 4.18). This is represented on the seismic by highly continuous, strong to weak amplitudes (e.g. Fig 4.17 and 4.20). The Triassic sequence is present in both the Sula-Sgier and Stack-Skerry sub-basins, where it truncates at the seafloor (e.g. Fig 4.3) or in some instances it is overlain by a veneer of quaternary deposits. The Triassic sequence has a maximum preserved thickness of 4200 m in the Sula-Sgier sub-basin.

There is only seismic evidence for the Sula-Sgier Fault being active during the Triassic, as divergence of reflections into the hanging-wall of the Sula-Sgier Fault can be observed (Fig 4.17 and 4.20). However, in the Stack-Skerry sub-basin, reflection divergence is difficult to judge (e.g. Fig 4.15 and 4.16), because the Triassic sequence is poorly preserved in the Stack-Skerry sub-basin.

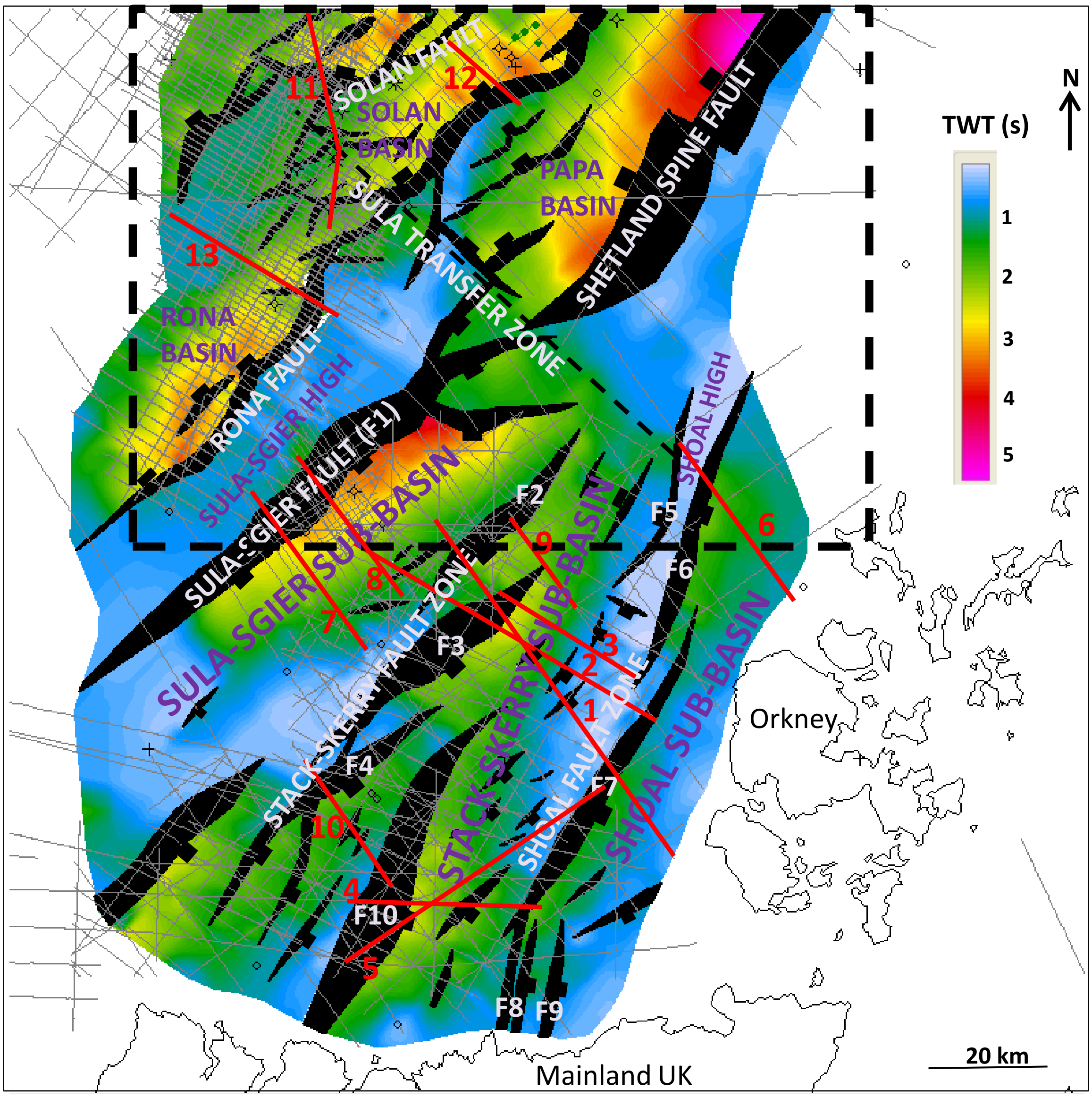
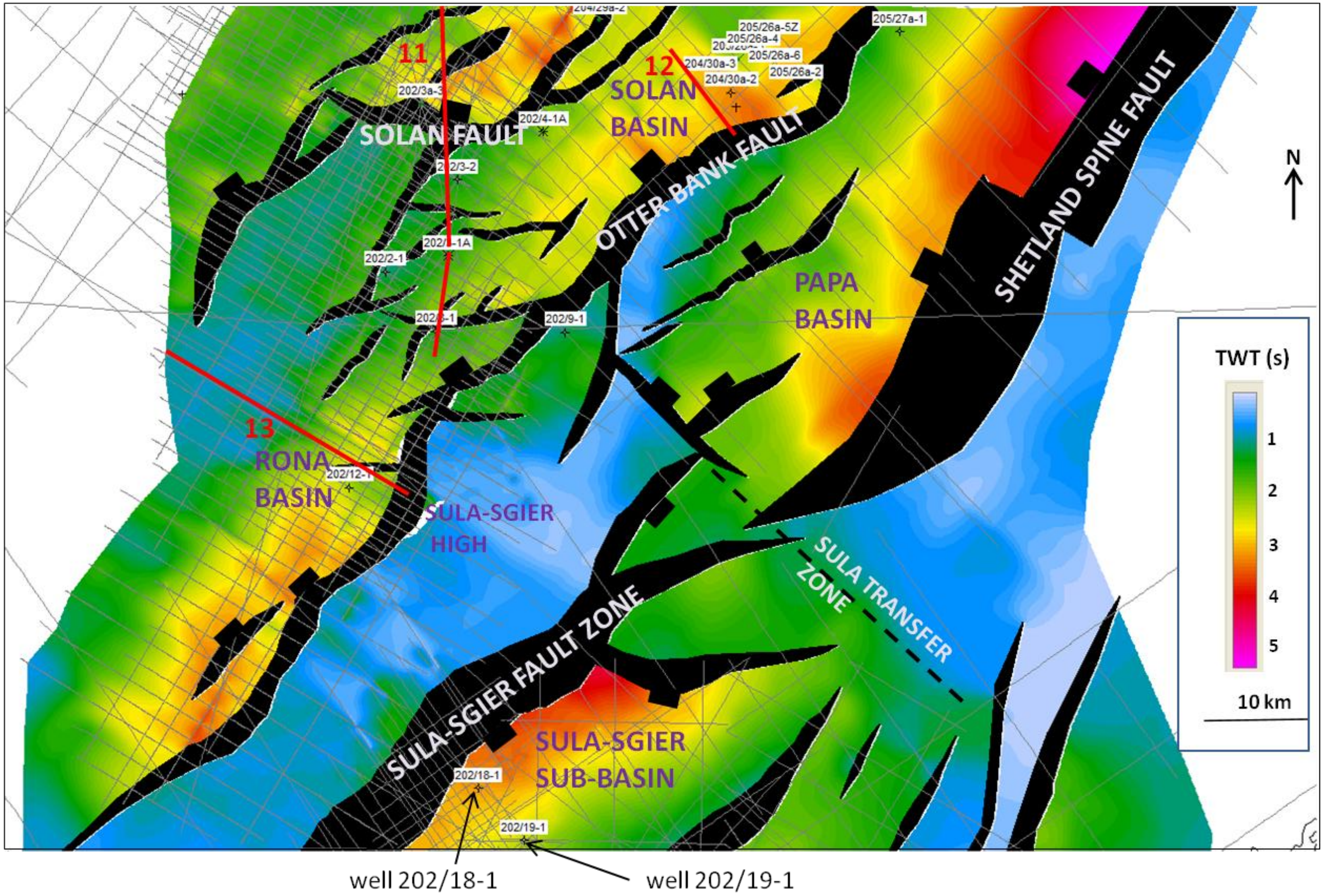


Figure 4-1. Structural interpretation of the top of the basement, as defined in Chapter 3. The major fault zones within the basin are used to subdivide the basin intro three sub-basins for basin analysis. The Shoal and Stack-Skerry Fault Zones are the western boundaries to the Shoal and Stack-Skerry sub-basins respectively, and in the west, the Sula-Sgier Fault is the western limit to the Sula-Sgier sub-basin. Dashed box shows location of Fig 4.2. Seismic lines discussed in text are labelled 1 to 13.



4-2. Structural interpretation of the top of the basement in the Rona, Solan and Papa Basins. Location of map is shown in Fig 4.1. Seismic lines discussed in text are labelled.

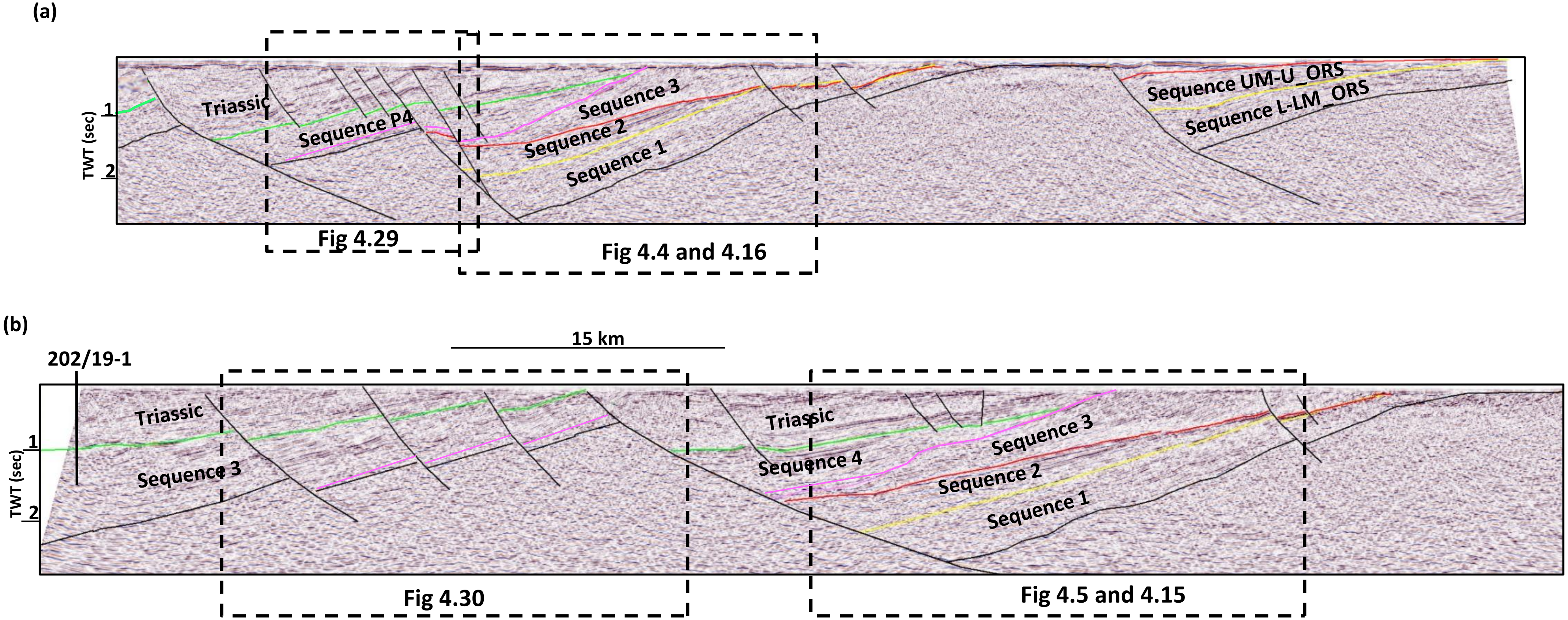


Figure 4-3. Five tectono-stratigraphic seismic sequences are distinguishable in the WOB. A sequence here is used as an informal term denoting a seismically recognisable package of distinctive reflection character. (a) Line 1, (b) Line 2. Locations of seismic lines are shown in Fig 4.1.

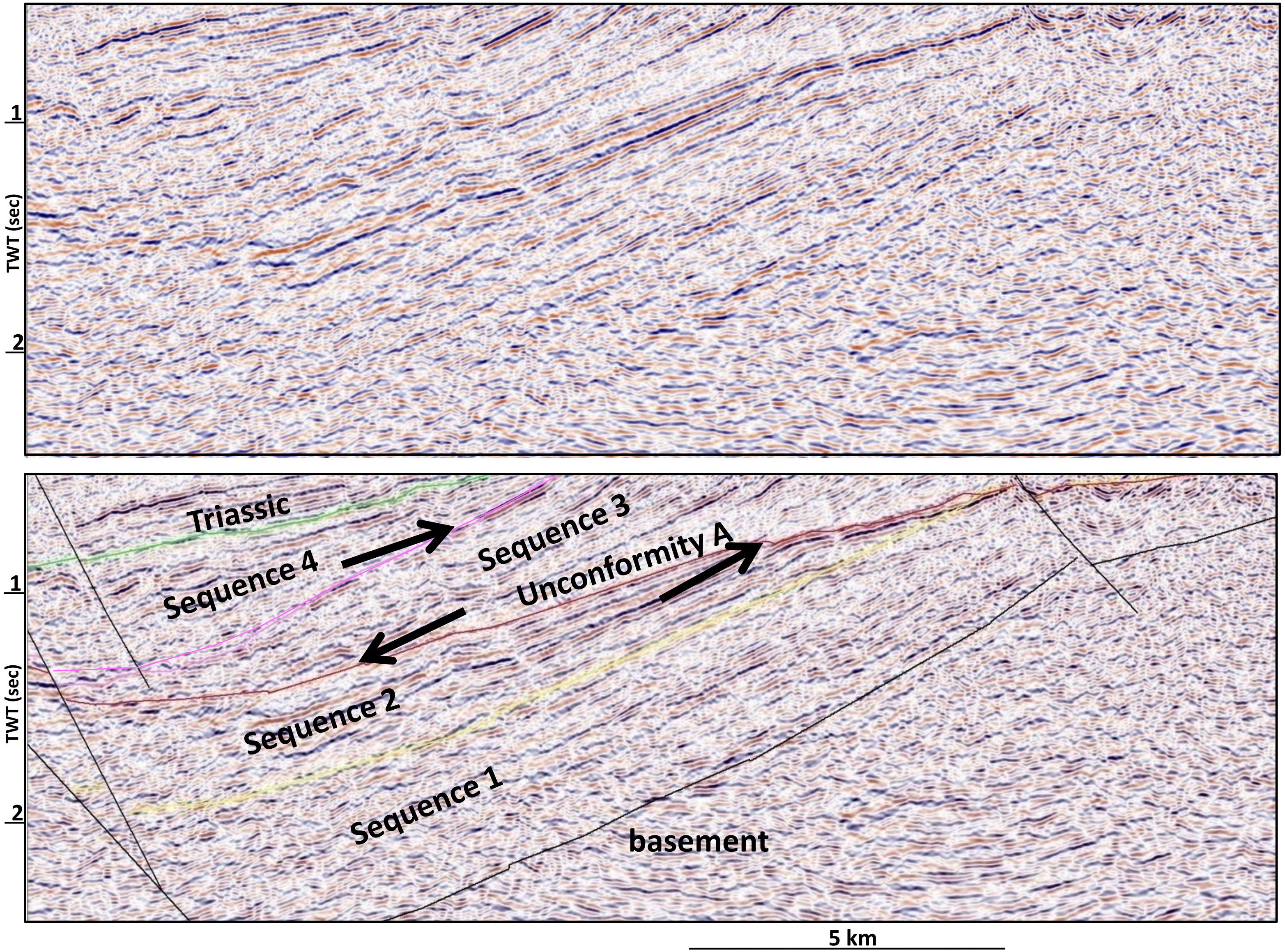


Figure 4-4. A portion of seismic line 1. For location see Fig 4.3.

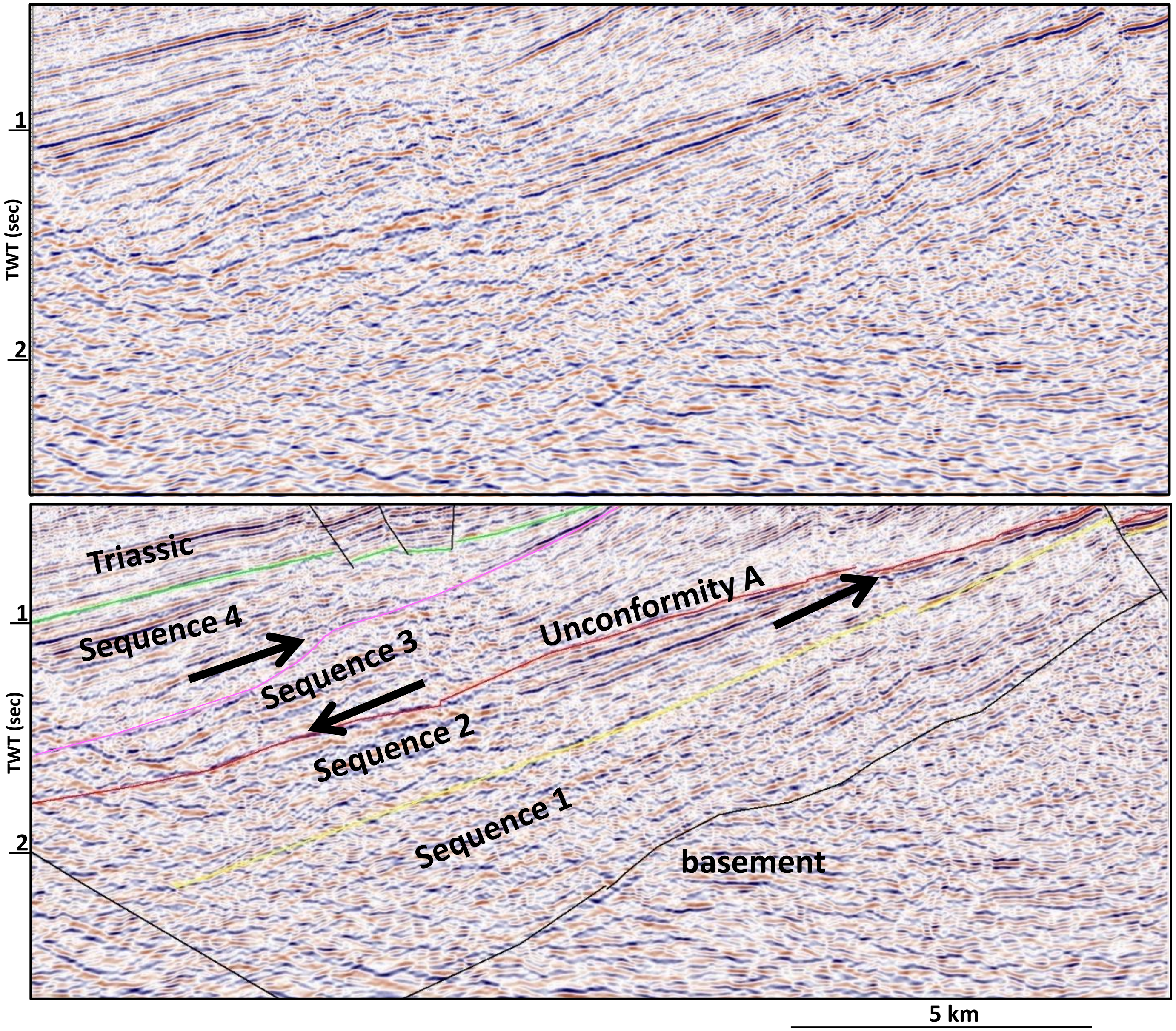


Figure 4-5. A portion of seismic line 2. For location see Fig 4.3.

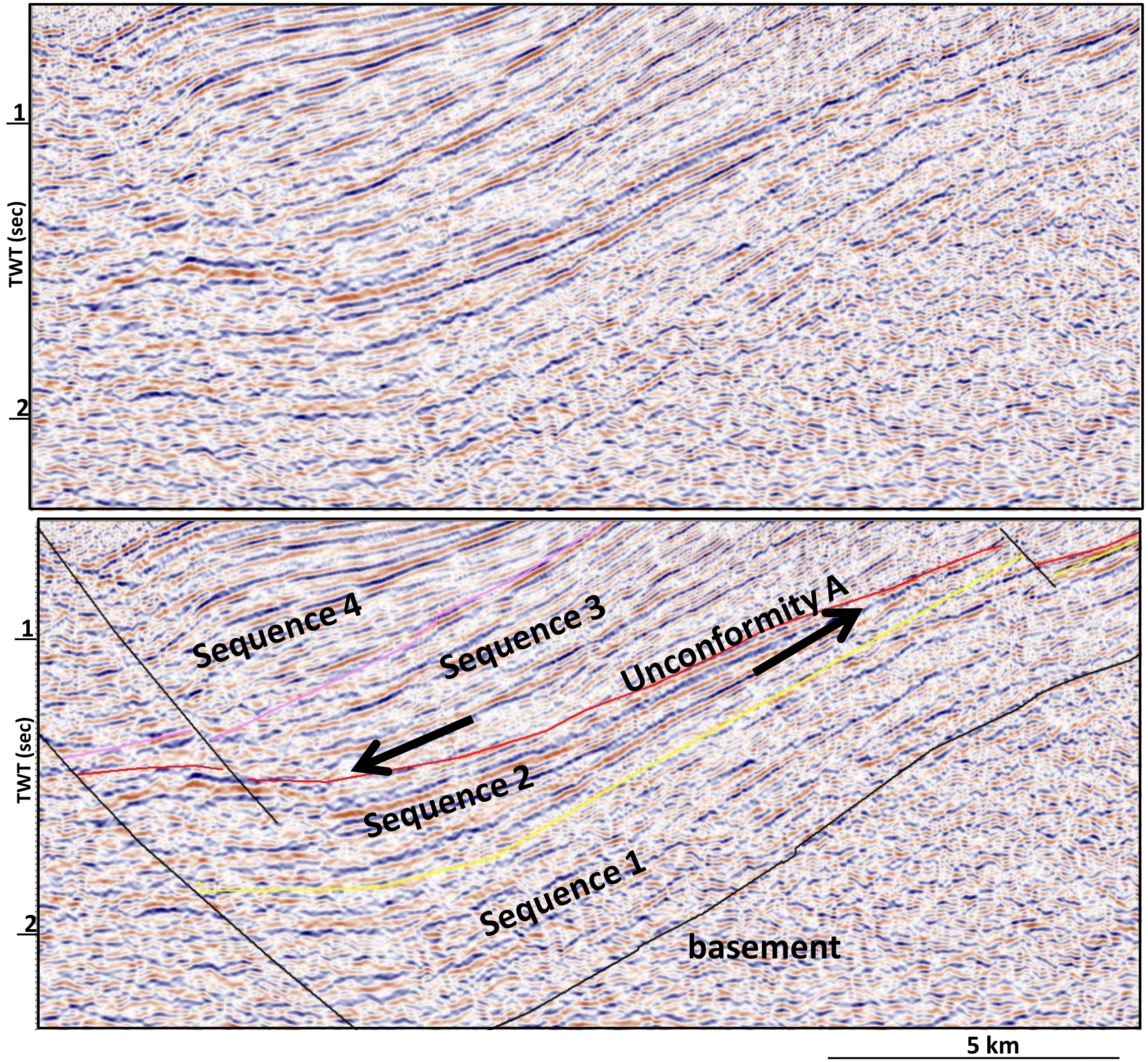


Figure 4-6. Interpretation of seismic line 3. Location is shown in Fig 1

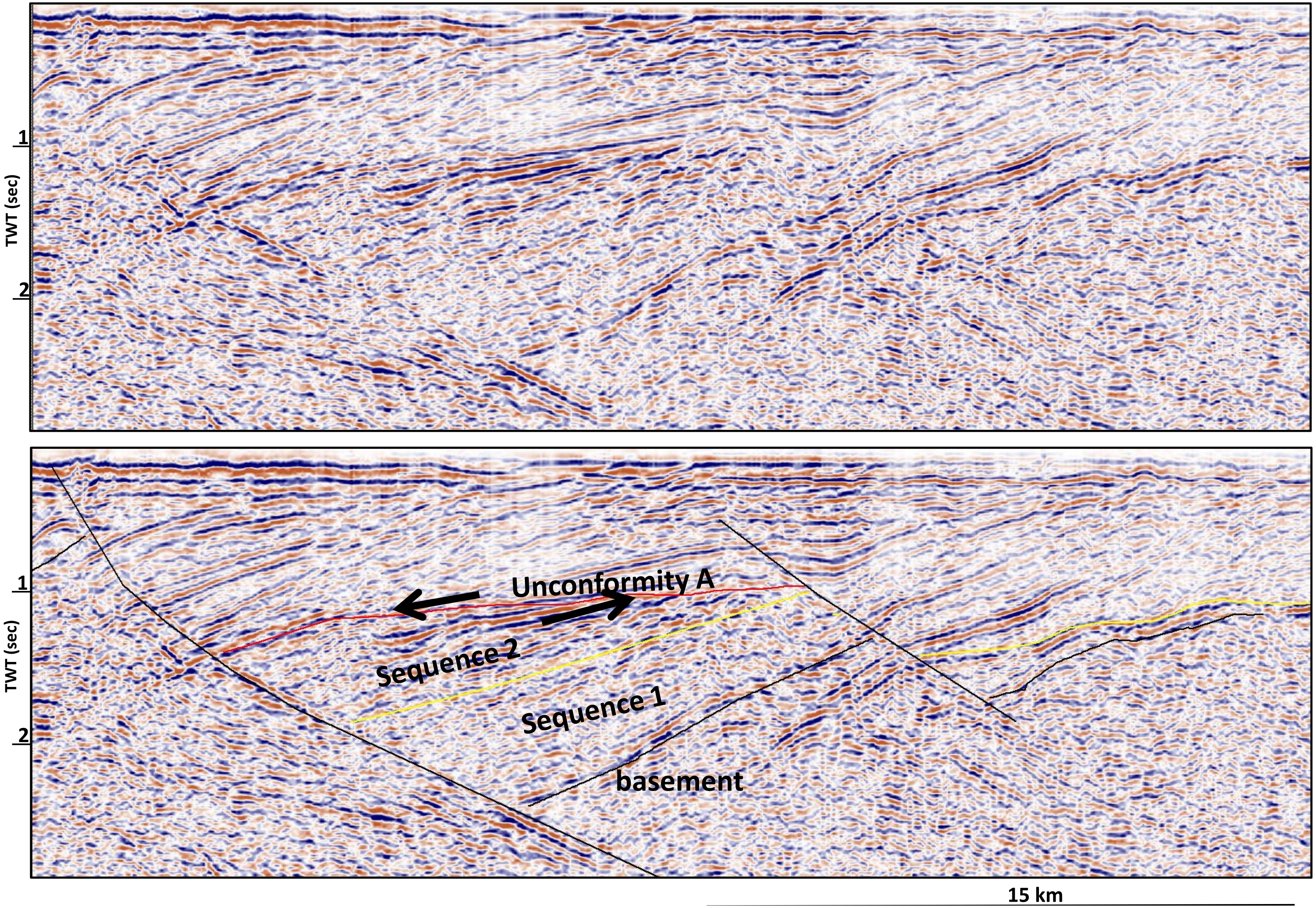


Figure 4-7. Interpretation of seismic line 4 (BIRPS deep crustal seismic line). Location shown in Fig 1

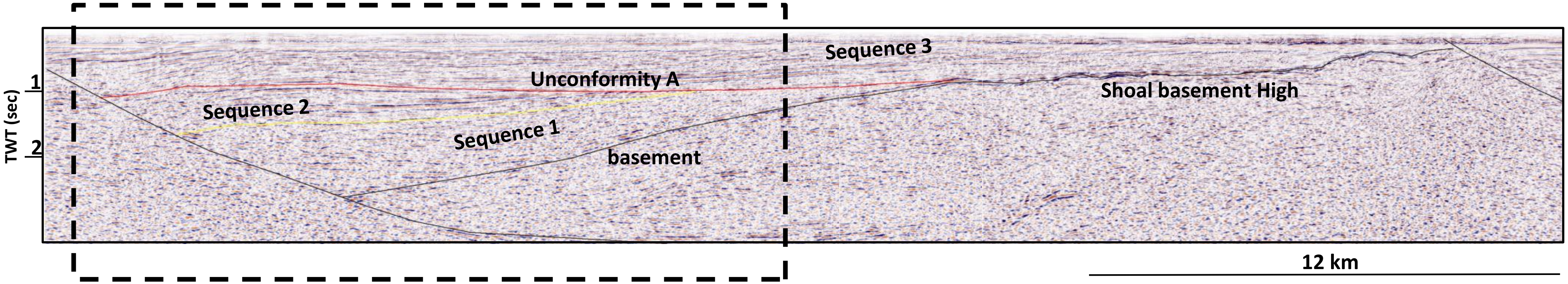


Figure 4-8. Interpretation of seismic line 5. Area shown in dashed boxed is presented in Fig 4.9. Location of line 5 is shown in Fig 1.

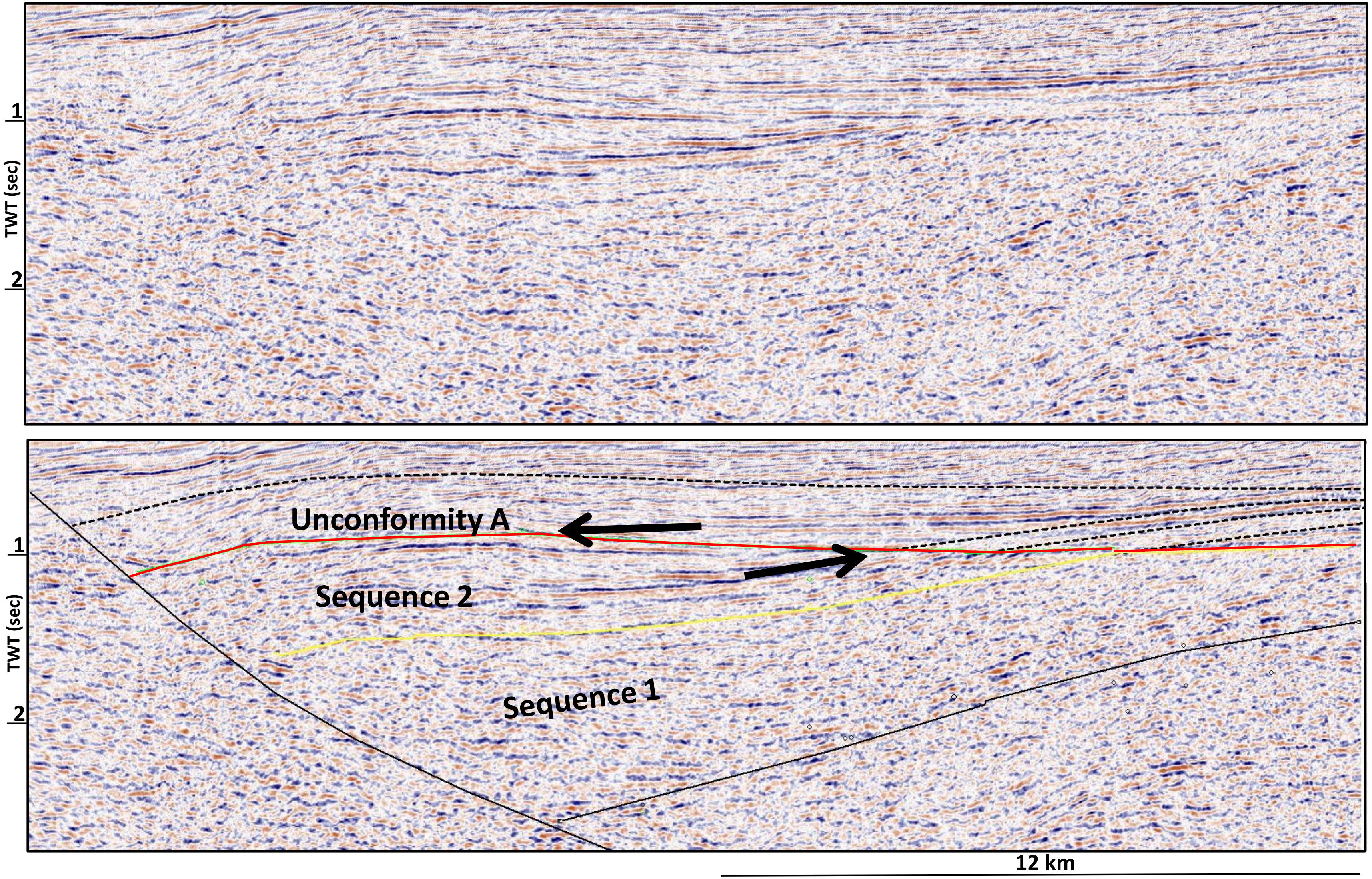


Figure 4-9. Interpretation of part of seismic line 5 - shown in Fig 4.8. Black dashed lines represent the inferred reconstructed eroded stratigraphy. The reconstruction suggests that about 300 to 1200 m of section was eroded at the L_CAR unconformity.

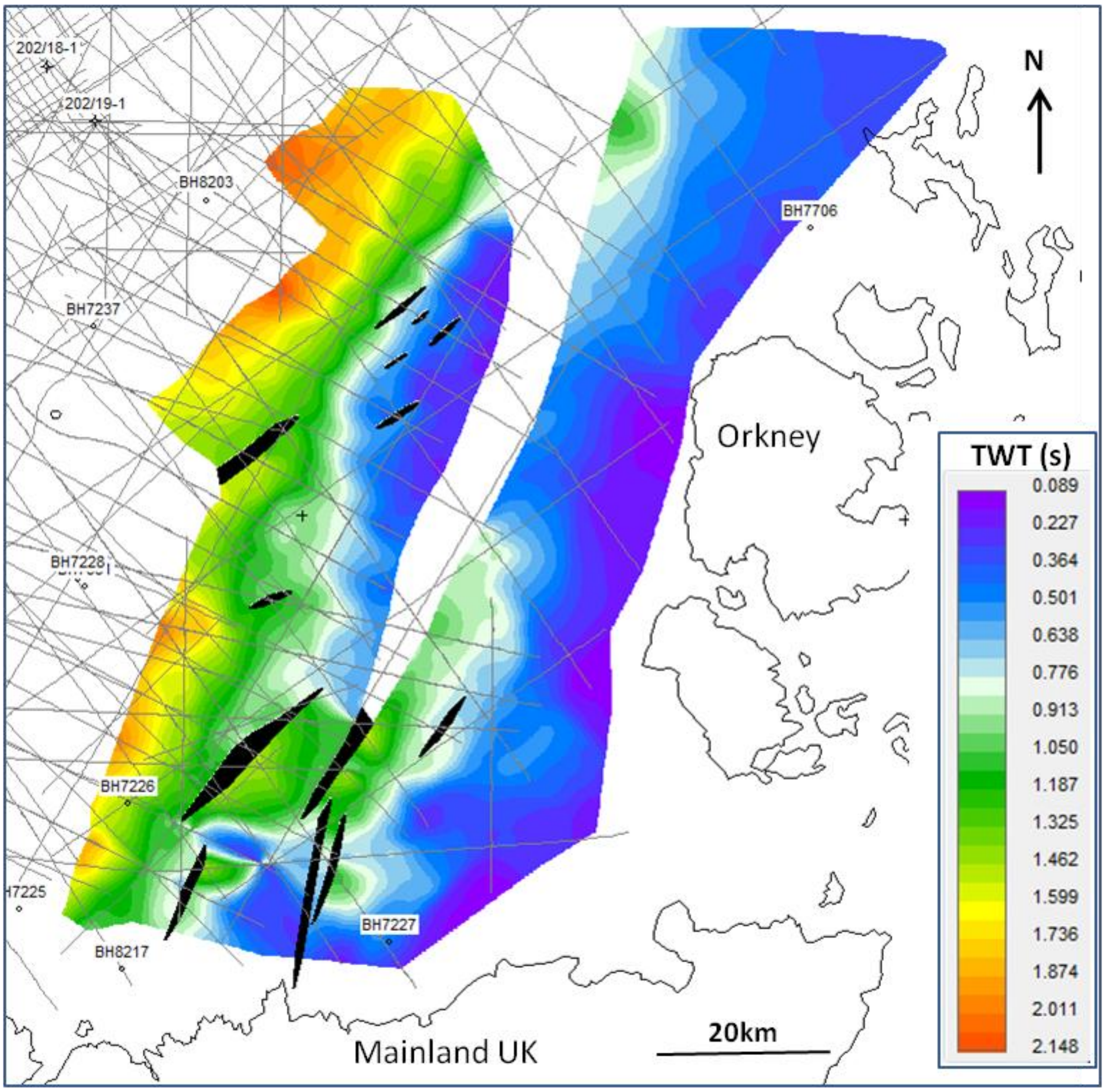


Figure 4-10. Structural map of the seismic facies boundary between Sequences 1 and 2.

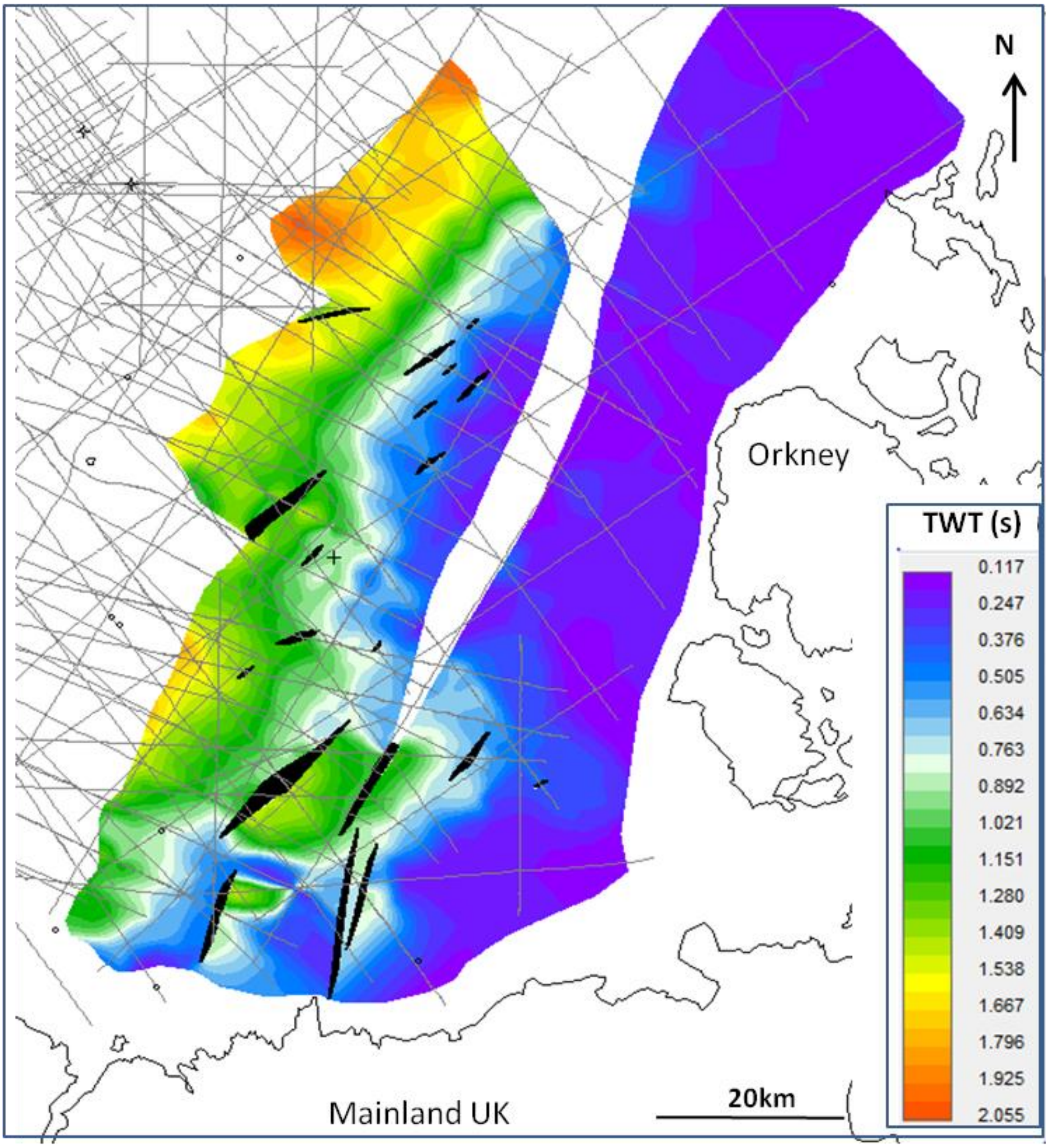


Figure 4-11. Structural map of Unconformity A.

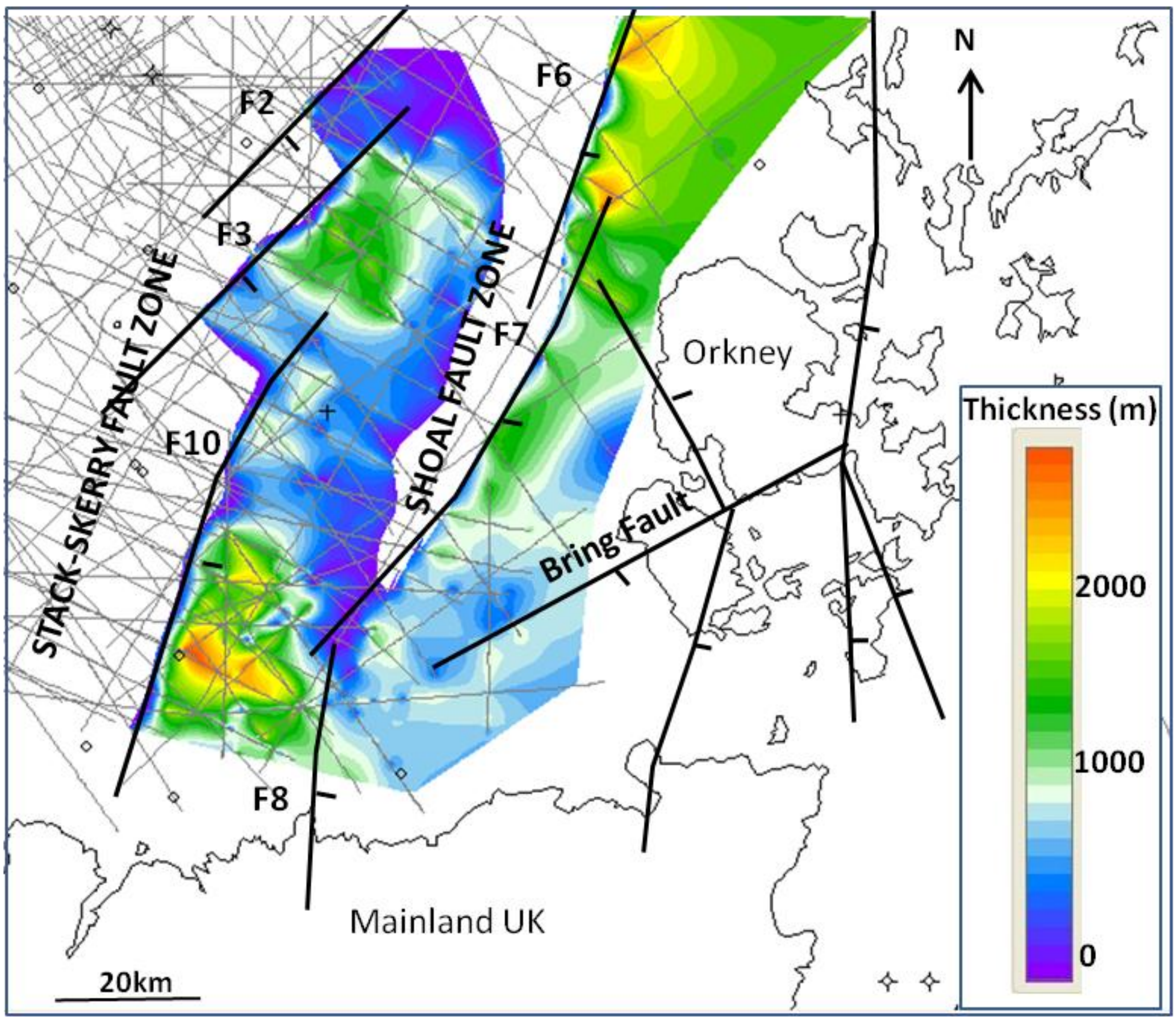


Figure 4-12. Isopach map of Sequence 1.

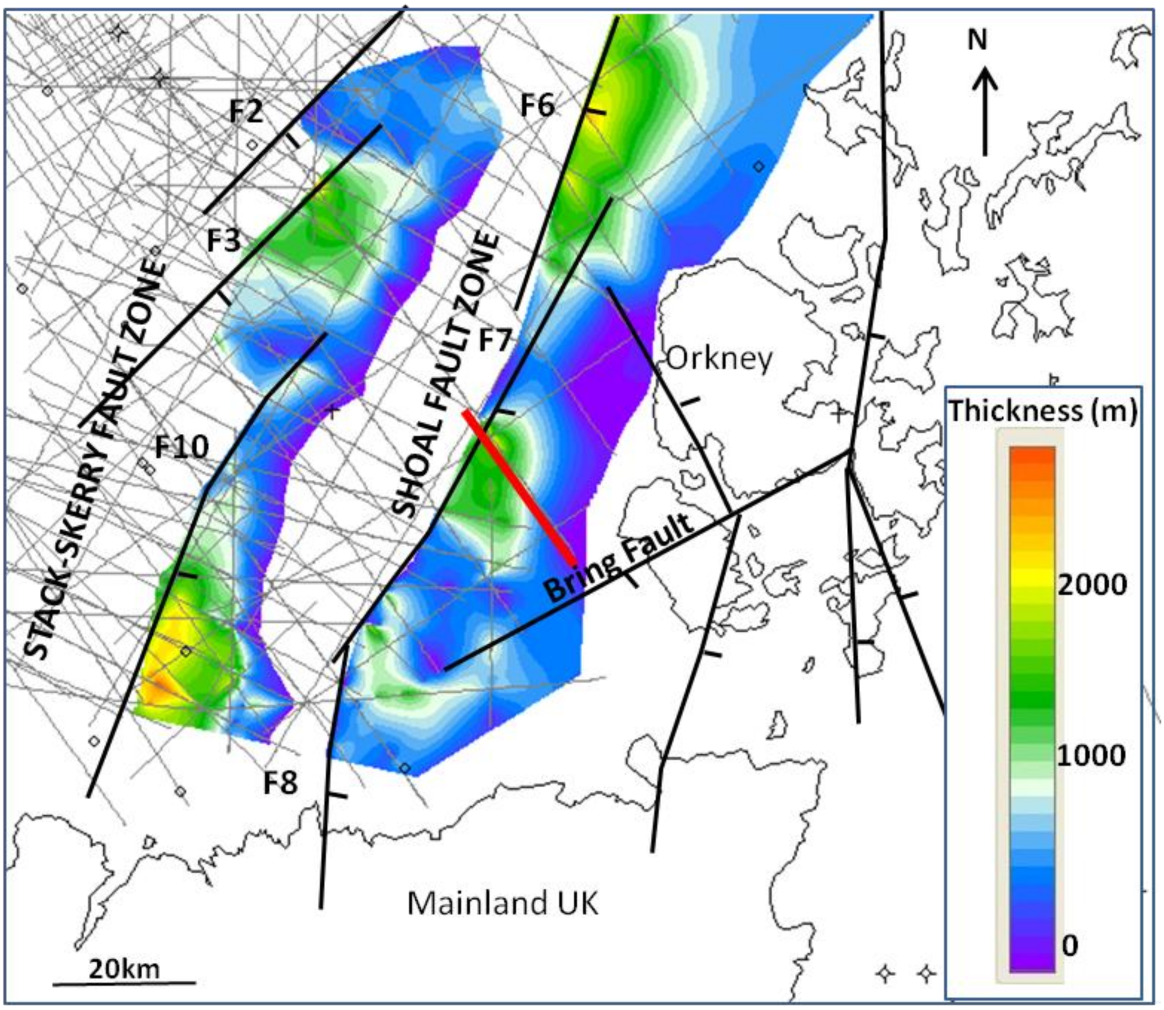


Figure 4-13. Isopach map of Sequence 2. Red line shows location of seismic line in Fig 4.23

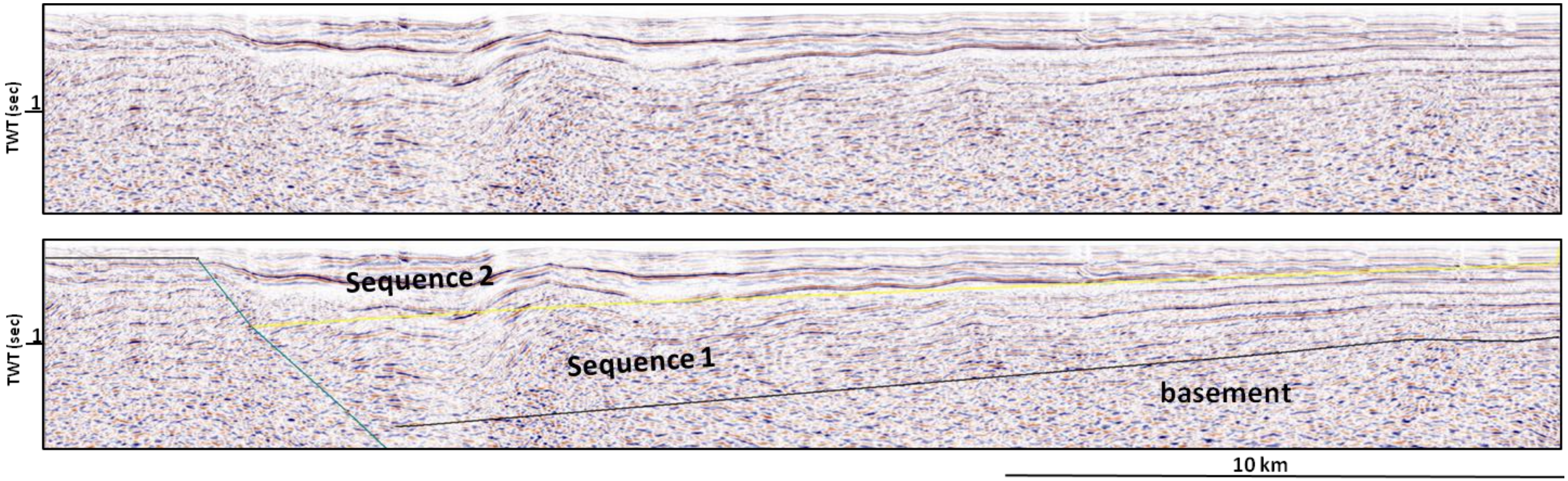


Figure 4-14. Interpretation of seismic line 6. Section is to illustrate the poor quality of the seismic in the northern extremities of the Shoal sub-basin. Location shown in Fig 1.

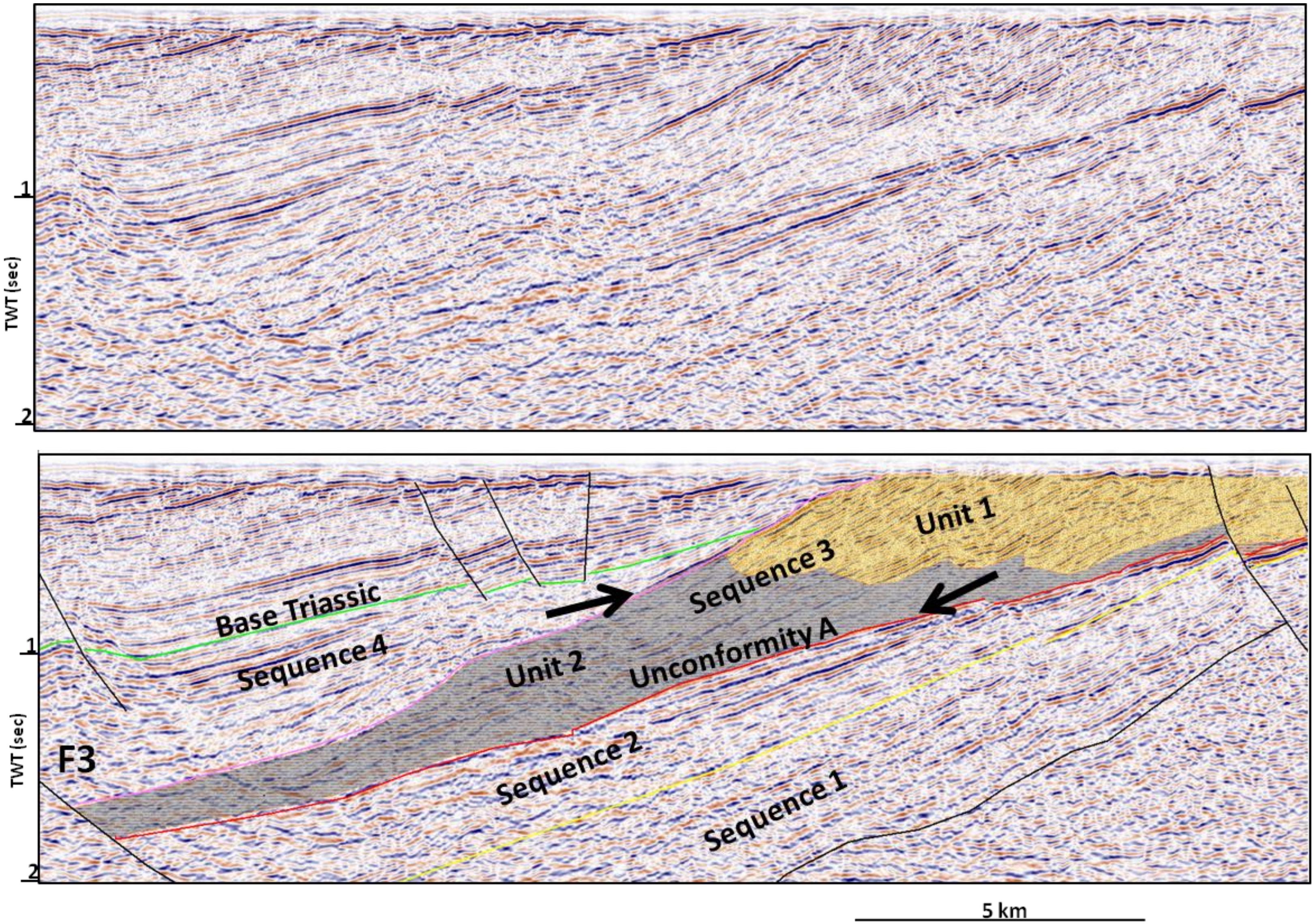


Figure 4-15. A portion of seismic line 2. Two different seismic facies units are distinguishable within Sequence 3. Unit 1 is coloured yellow and Unit 2 is Gray coloured. For location see Fig 4.1.

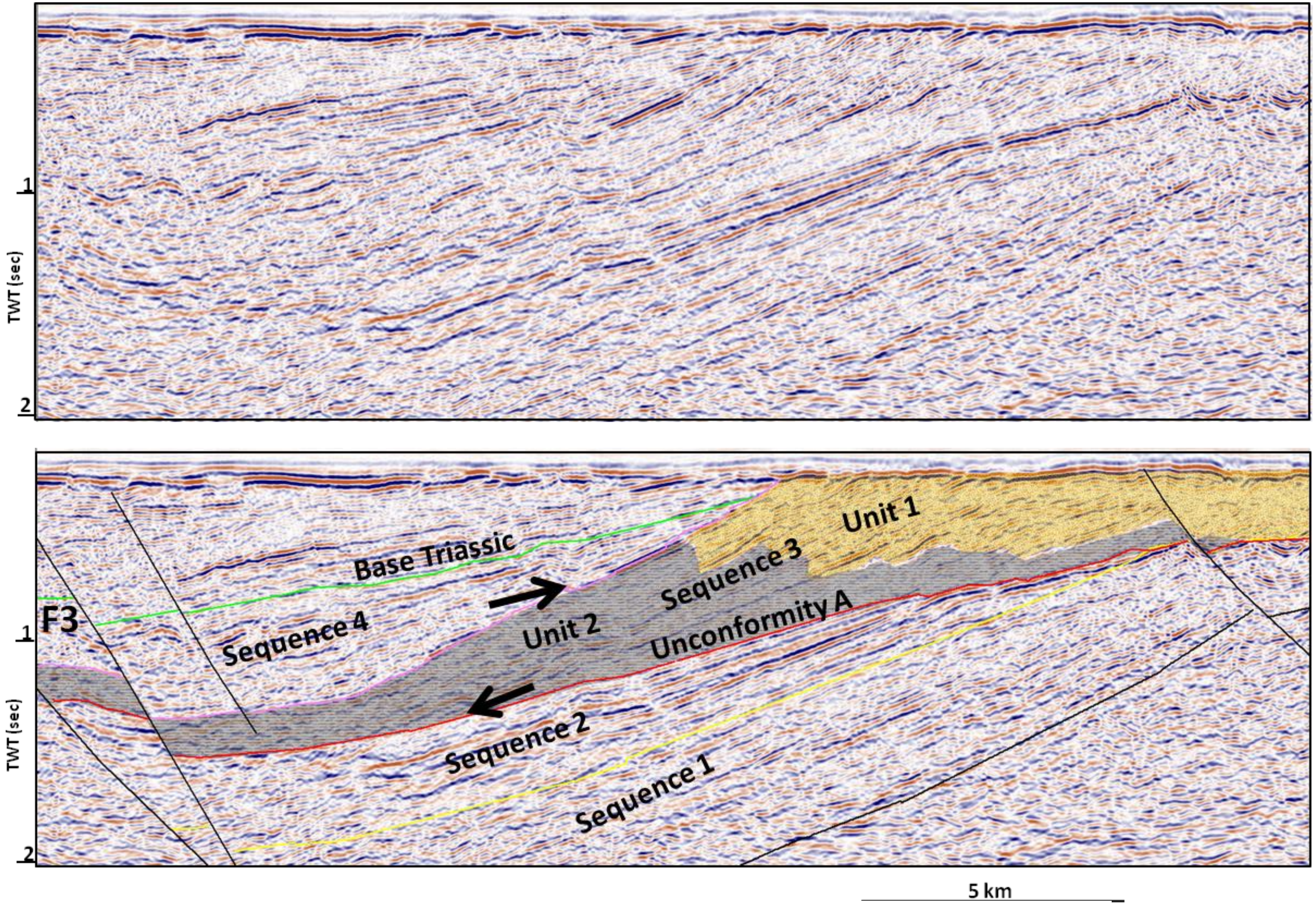


Figure 4-16. A portion of seismic line 1. Two different seismic facies units are distinguishable within Sequence P1. Unit 1 is coloured yellow and Unit 2 is Gray coloured. For location see Fig 4.1.

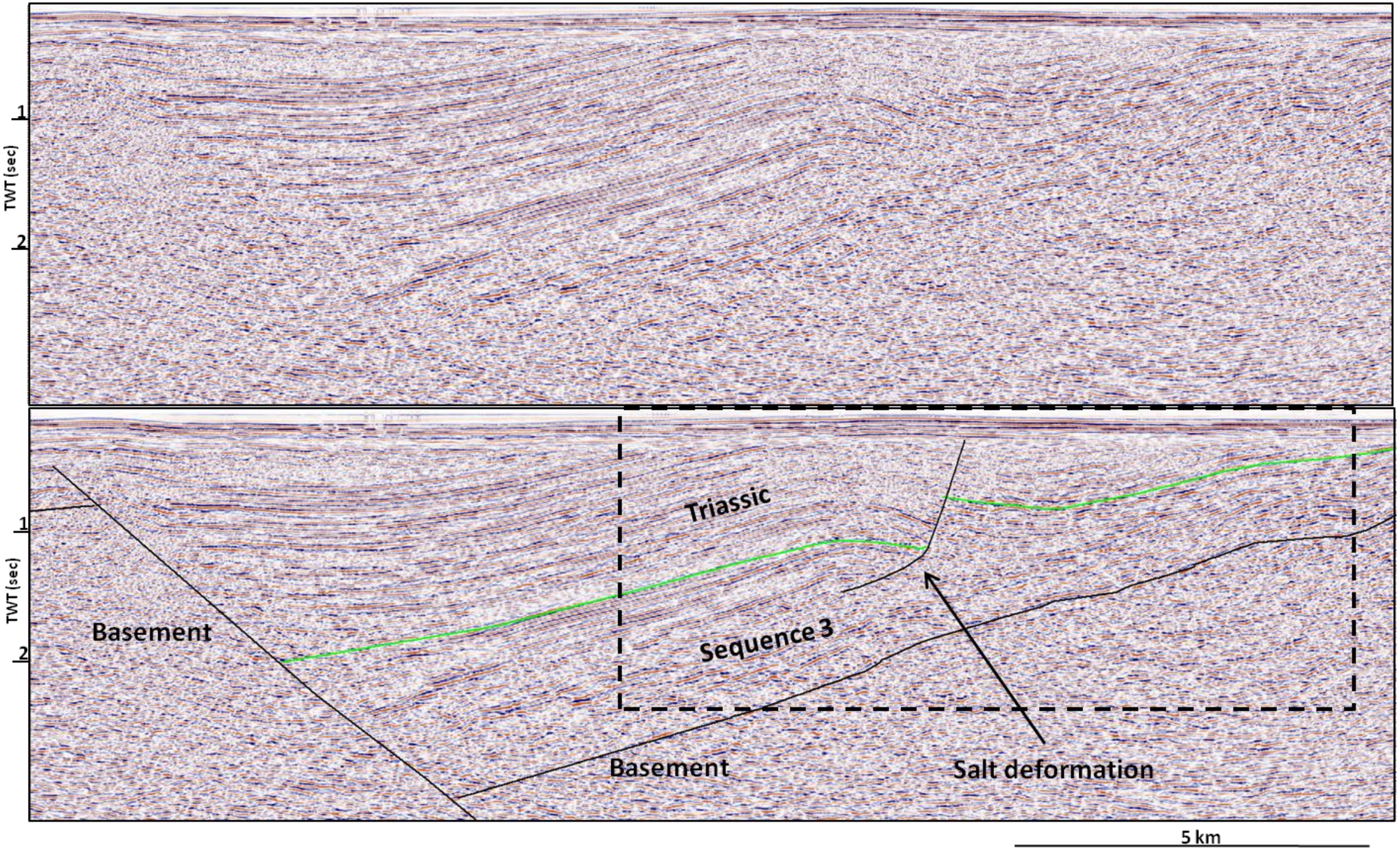


Figure 4-17. Interpretation of seismic line 7. Antithetic fault is interpreted to detach into the upper portion of Sequence 3 (evaporites), with associated roll-over fold. Area shown in dashed box is illustrated in Fig 4.19. For location see Fig 4.1

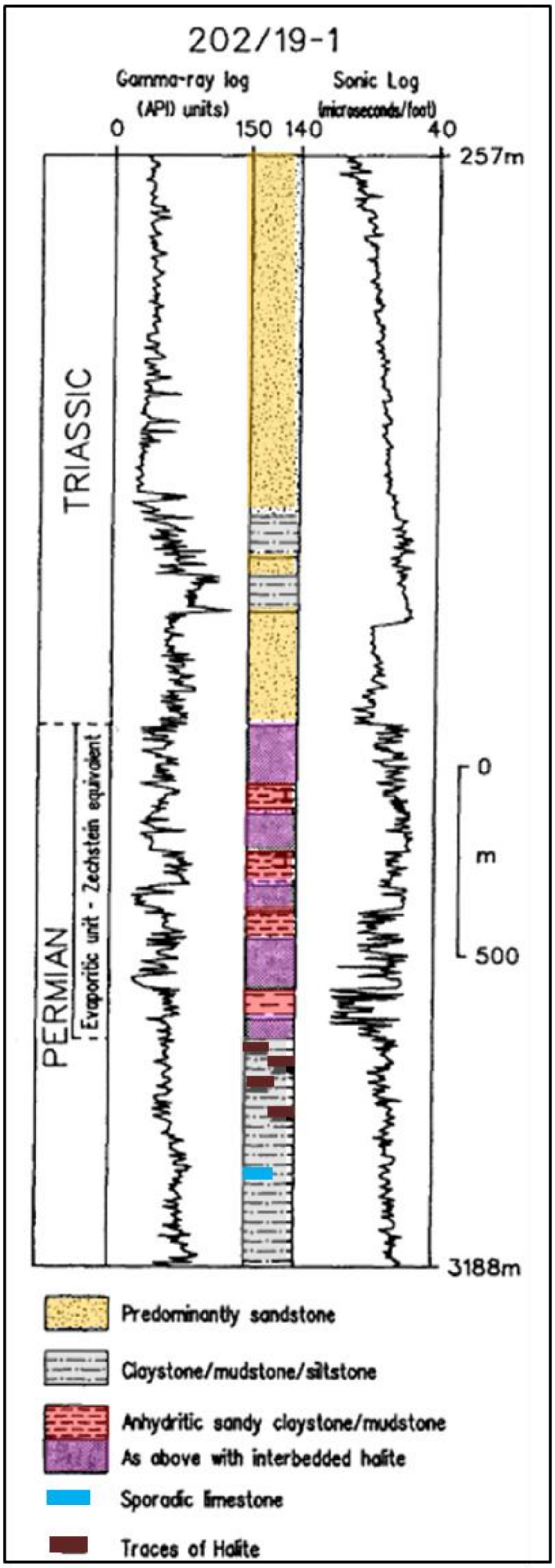


Figure 4-18. Exploration well WOB 202/19-1. The deepest well drilled in the WOB, which encountered a Permo-Triassic sequence. Lithology interpretation is taken from the comp log (Hitchen et al. 1995). Location of well is shown in Fig 4.2 and 4.3.

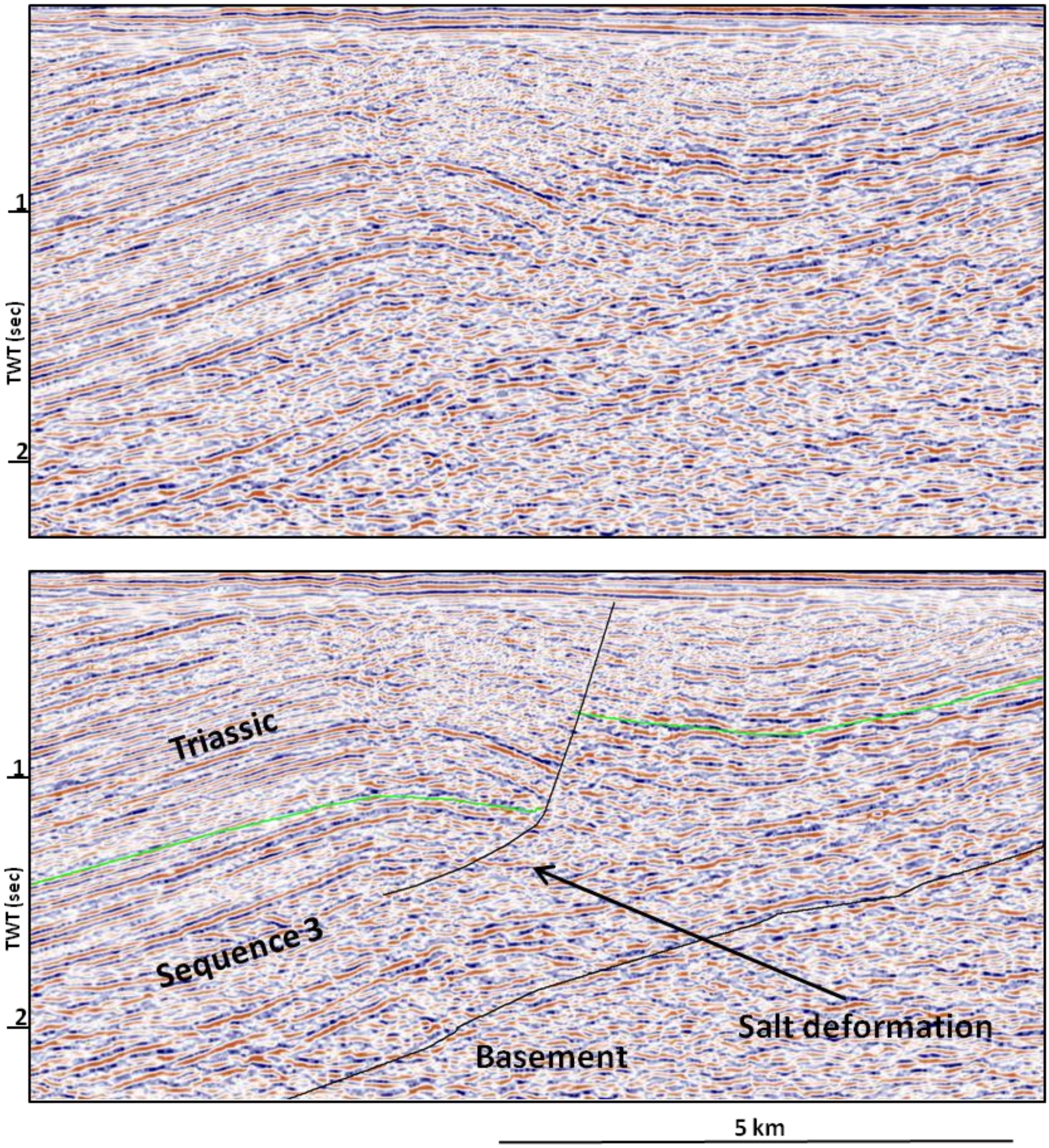


Figure 4-19. Interpretation of the area shown in dashed box in Fig 4.17. Antithetic fault is interpreted to detach into the upper portion of Sequence 3 (evaporites).

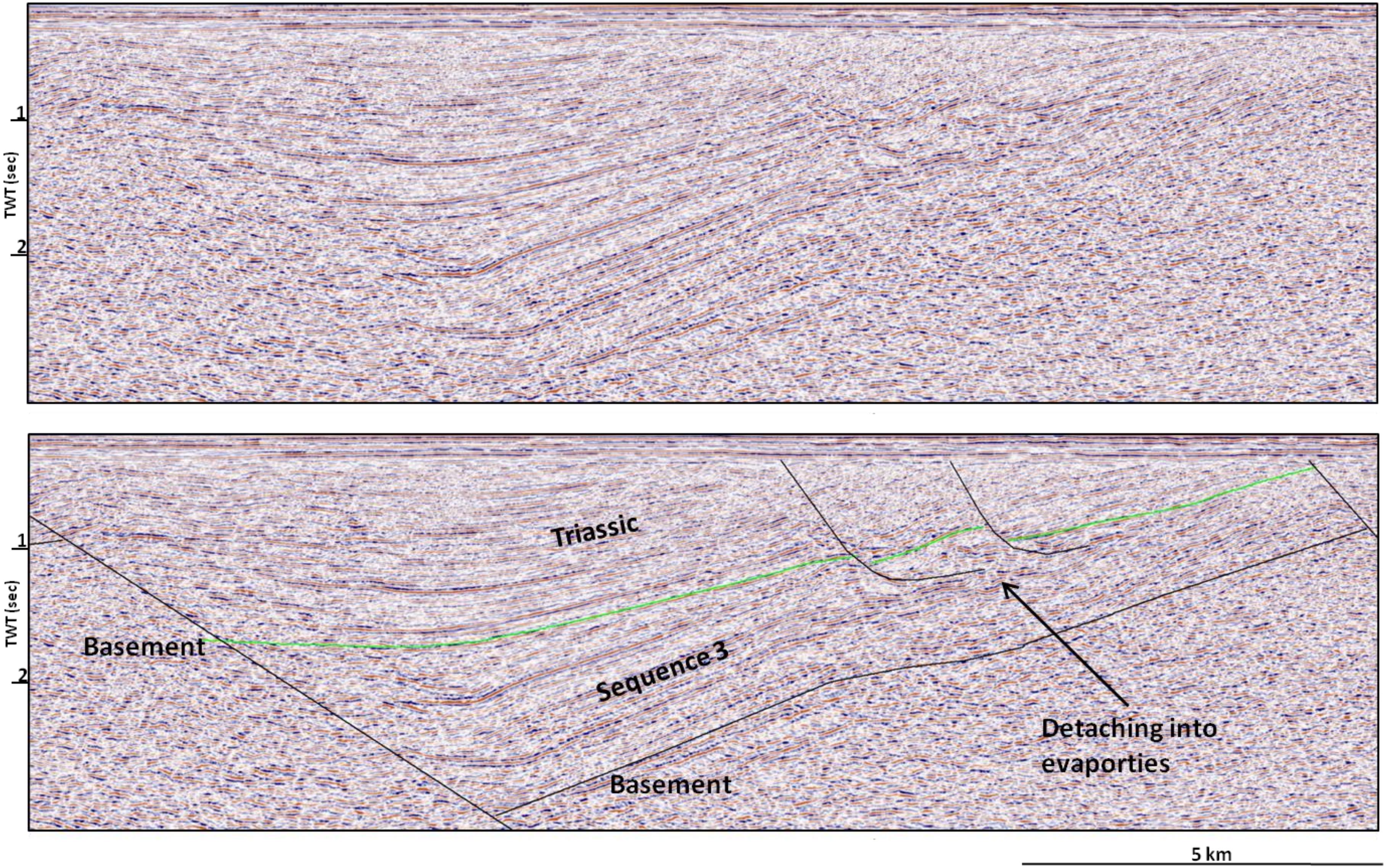


Figure 4-20. Interpretation of seismic line 8. For location see Fig 4.1. Note faults detaching into the top of Sequence 3.

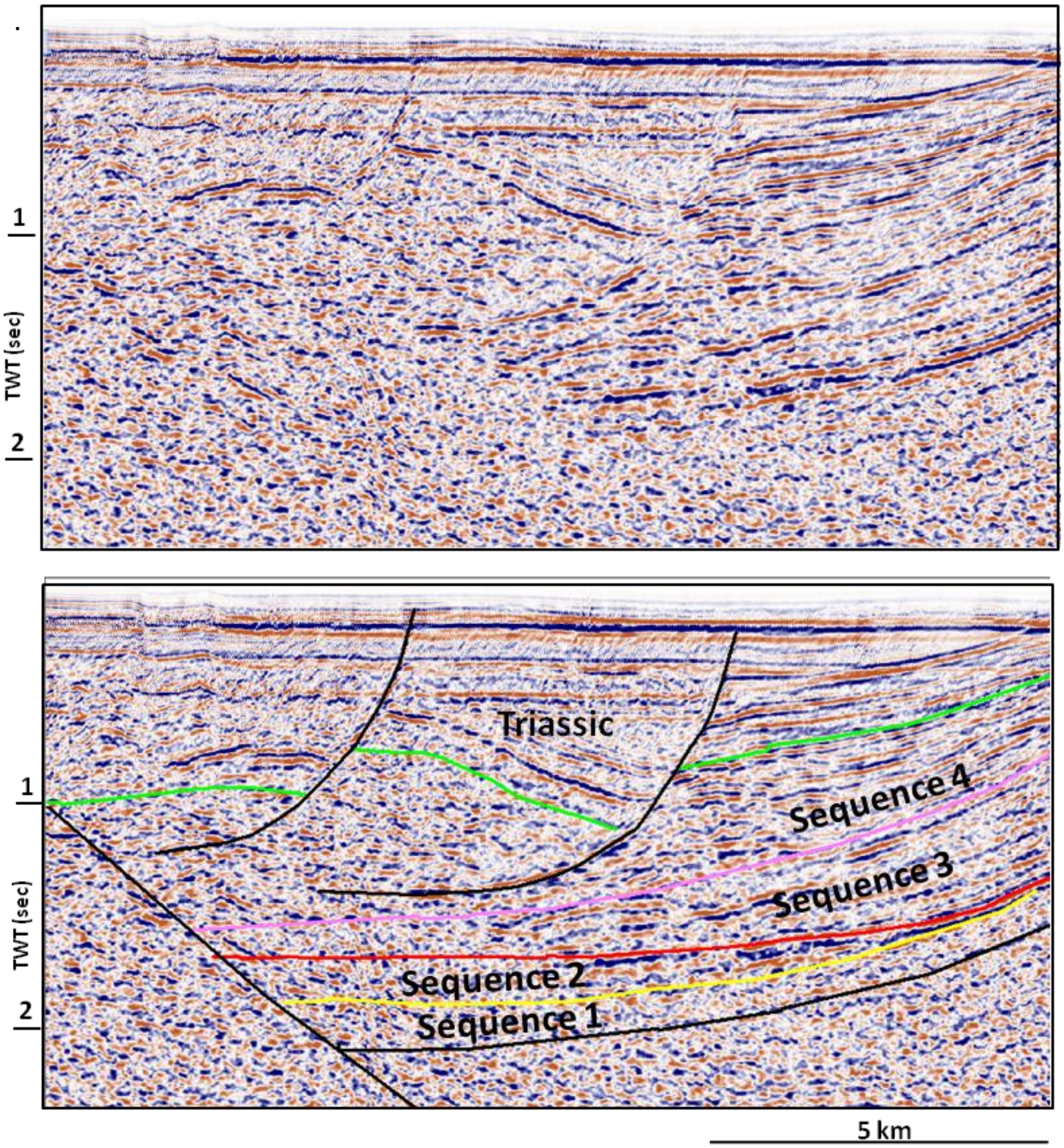


Figure 4-21. Interpretation of seismic line 9. Antithetic faults are interpreted to detach into the upper portion of Sequence 3 (evaporites). For location see Fig 1.

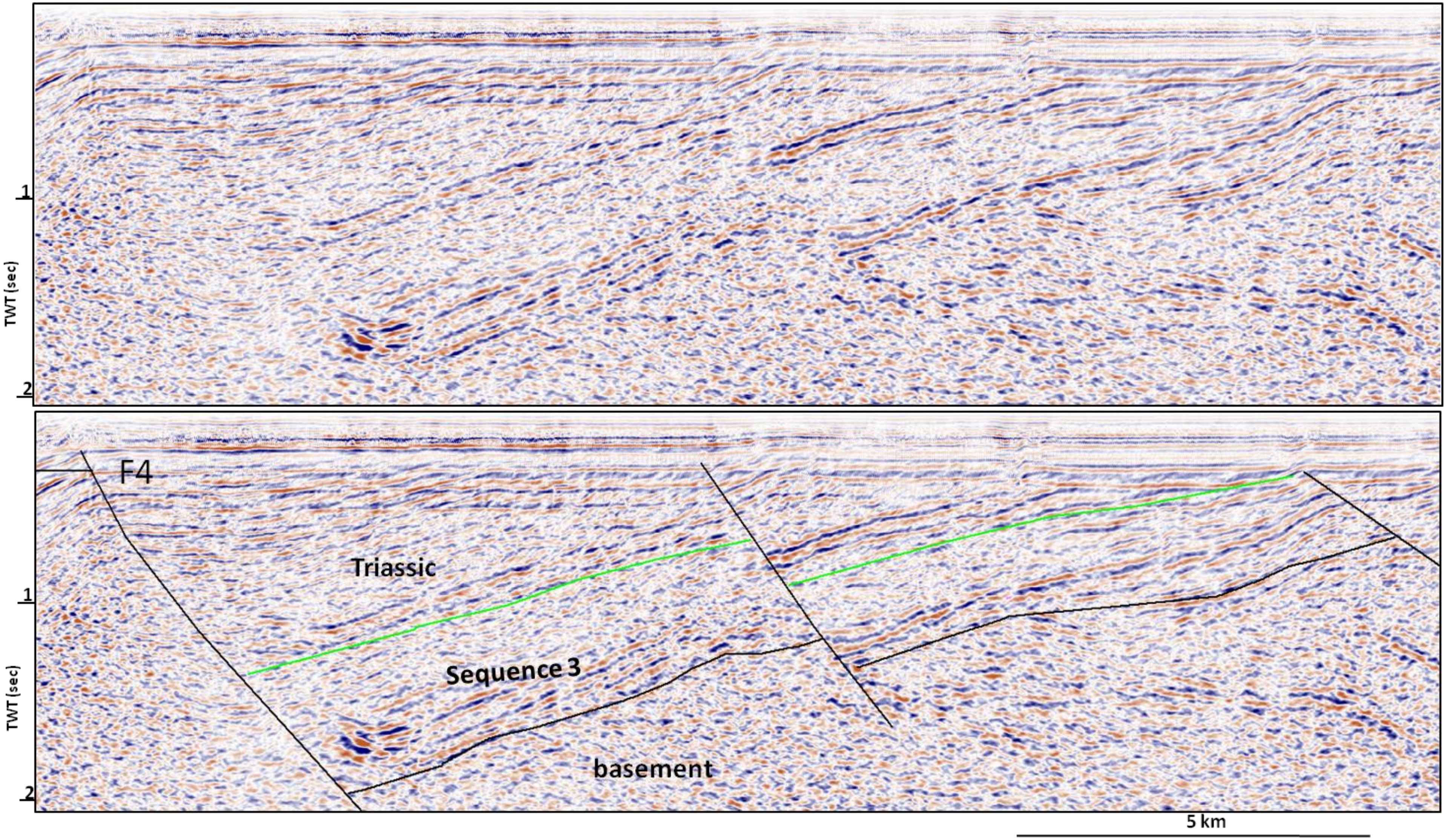


Figure 4-22. Interpretation of seismic line 10. For location see Fig 1.

4.2.2 Interpretation of the age of the sedimentary fill within the WOB

The mapped position of Unconformity A (Figs 4.3 to 4.9) corresponds closely to previous interpretations (e.g. Chapter 1: Coward & Enfield 1987; Earle et al. 1989; Stocker et al. 1993; Wilson et al. 2010), who described it as an onlap surface. Wilson et al. (2010) suggested that it represents a regional unconformity, which is locally conformable, and went onto interpret it as being the contact between Lower-Middle Devonian and Upper Devonian. The results from this work presents an alternative interpretation to these previous studies, because regional erosional truncation of 100s – 1000s of metres plus has been observed at Unconformity A during this study (e.g. Figs 4.3 to 4.9), and therefore, it is suggested here that it is unlikely to represent the boundary between Lower-Middle Devonian and Upper Devonian. The reason for this disagreement is that within the onshore areas of the WOB and elsewhere in the Orcadian Basin, the entire Devonian succession is conformable, with only locally developed unconformities (e.g. Rogers et al. 1989; Marshall et al. 1996).

Thus, it is here argued that the most plausible interpretation for the age of Unconformity A is that it is related to Late Carboniferous dextral inversion (Variscan Orogeny) of the Great Glen-Walls Boundary fault system (e.g. Seranne 1992) and associated regional uplift, since this represents the only event within the Devonian to Triassic period, where regional uplift and erosion of the magnitude observed in the study area has previously been documented (e.g. Seranne 1992; Hippler 1993; Duncan & Buxton 1995). Therefore, below the unconformity, Sequences 1 and 2 (which represent the first phase of rifting in the WOB), are most likely Devonian to Early Carboniferous age. Regional Late Carboniferous uplift and erosion of Devonian sequences is well documented from other locations within the Orcadian Basin (e.g. Inner Moray Firth basin: Marshall (1998); Shetland Platform: Serrane (1992)).

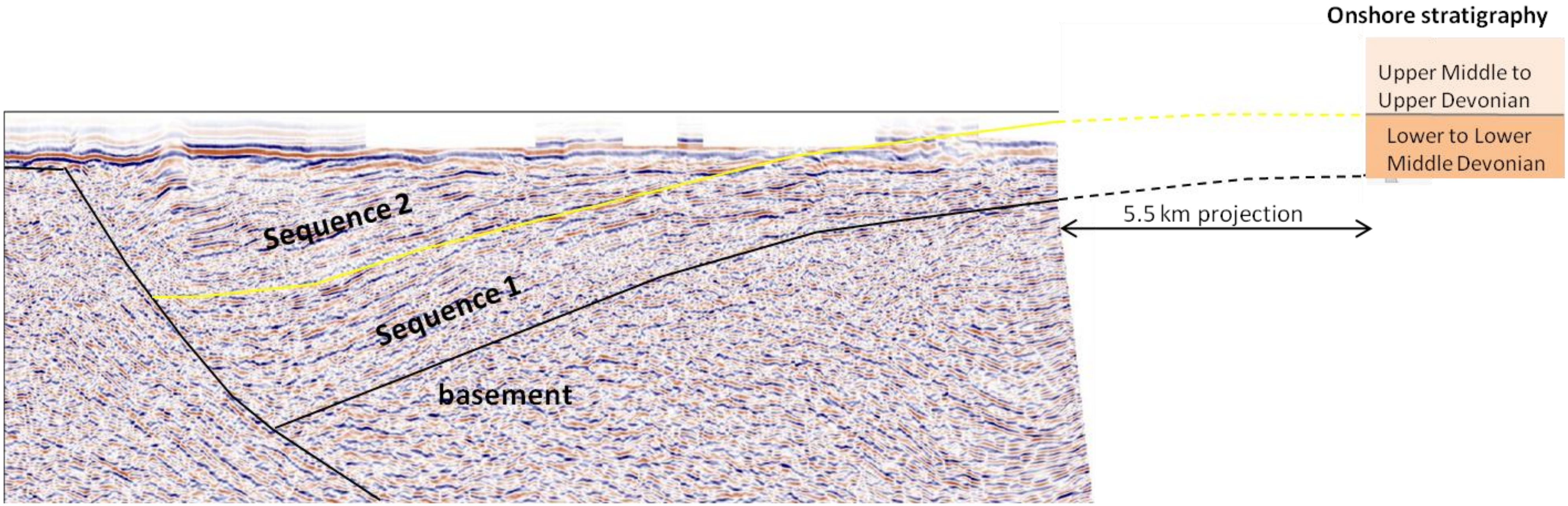


Figure 4-23. Portion of seismic line 1, showing the onshore projection (to Orkney) of the boundary between Sequences 1 and 2. The boundary correlates with the onshore stratigraphic contact between Lower to Lower Middle and Upper Middle to Upper Devonian. Location of the seismic line in relation to the onshore is shown in Fig 4.13.

Supporting the argument for a Late Carboniferous age for Unconformity A is that the mapped seismic Sequences 1 and 2 appear to be structurally continuous with Devonian outcrops on Orkney (e.g. Fig 4.3a and 4.23). Additionally, the characteristic seismic facies of Sequences 1 and 2 is correlatable with the lithofacies of Lower to Lower Middle and Upper Middle to Upper Devonian respectively in the onshore areas of the WOB; since the thinly bedded 'hard' lacustrine sequence, which dominates the outcropping lower to lower middle Devonian (e.g. Astin 1990), would most likely give a more weak to almost opaque seismic signature (15 to 25 Hz seismic frequency) when compared to the upper middle to upper Devonian (e.g. Figs 4.3 to 4.9), because it is composed of thick homogenous sand units.

The boundary between Devonian and Carboniferous rocks is poorly defined in this area of the NE Atlantic margin, because arid to semi-arid continental deposition occurred in both Devonian and Early Carboniferous times (Bruce & Stemmerik 2003). It is possible that outcrops of what are thought to be Upper Devonian fluvial sands on Orkney and in northern Scotland could in fact be as young as Early Carboniferous. However, with the lack of definitive fossil assemblages, the age remains conjectural (Trewin 2002). Therefore, it is considered at least possible that the uppermost part of Sequence 2 could be Early Carboniferous in age.

The western boundary to deposition of Sequences 1 and 2 appears to have been controlled by Faults 2, 3 and 10 of the Stack-Skerry Fault Zone (e.g. Fig 4.12 and 4.13), and therefore this may represent the western boundary to the Orcadian Basin (Fig 4.24). Bird et al. (2015) has proposed that the Stack-Skerry Fault Zone forms an oblique and partially exploitative relationship with pre-rift Caledonide basement

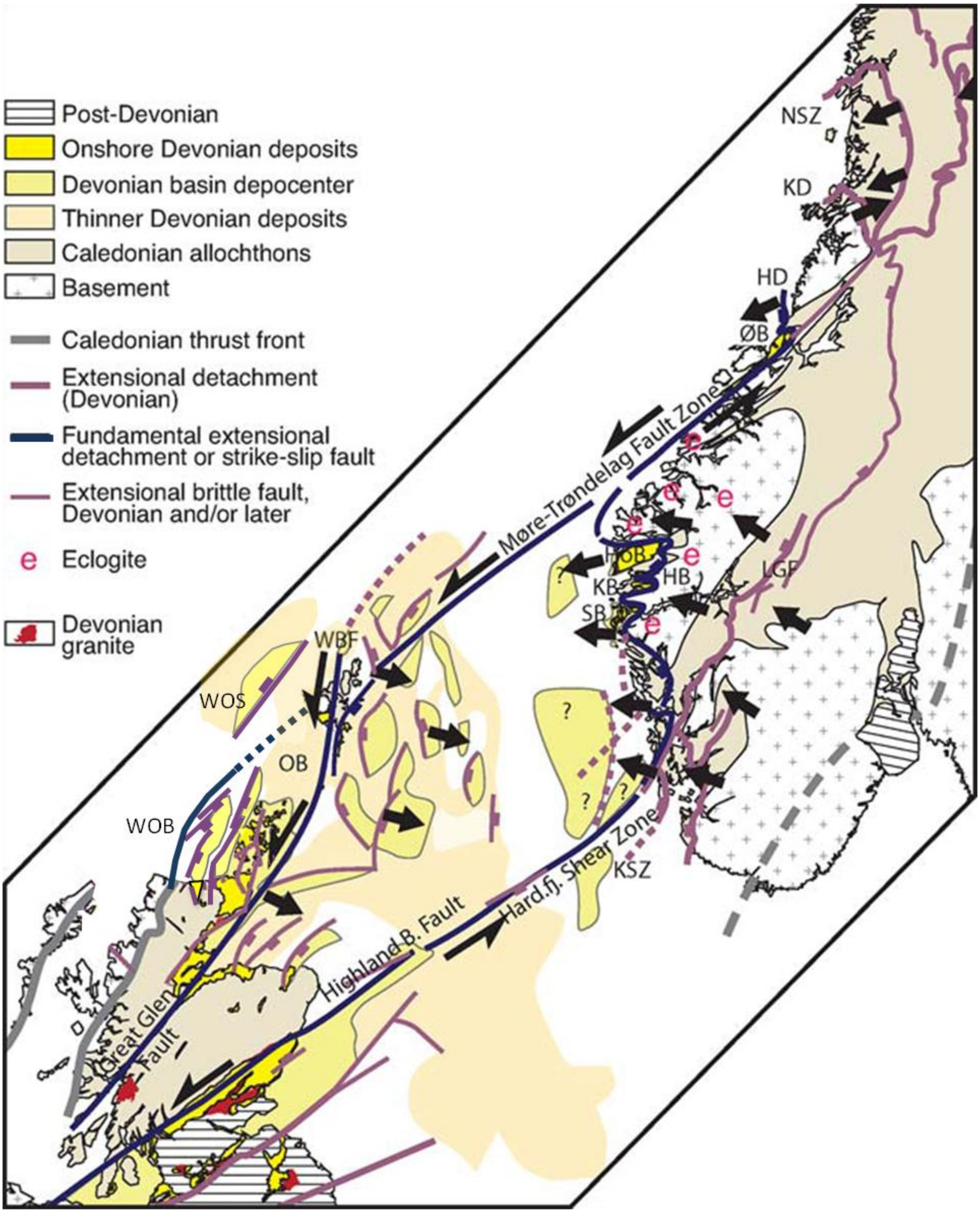


Figure 4-24. Diagram of a Devonian transtensional model for the formation of the Orcadian Basin (modified from Fossen 2010). The Stack-Skerry Fault Zone is interpreted as the western tectonic-boundary to the Orcadian Basin. Abbreviations – OB: Orcadian Baisn, WOB: West Orkney Basin, WOS: West of Shetland Basin

structure. This may support a Devonian extensional model for formation of the Orcadian Basin that is best explained by rifting associated with sinistral-transtension along the Great Glen-Walls Boundary Fault and Highland Fault system (Fig 4.24) (e.g. Seranne 1992; Dewey 2003; Watts et al. 2007; Fossen 2010), than opposed to models that only convey simple relaxation (extensional-backsliding) of an over thickened Caledonian crust (e.g. McClay et al. 1986; Norton 1987).

The depositional geometry of the characteristic eastward thickening package (Sequence 3) apparent on seismic within the WOB can be analysed by structurally restoring the eroded section of Sequence 3 (Fig 4.25). The restored geometry of the stratal configuration (convergent downlap geometries) and the seismic facies of Units 1 and 2 within Sequence 3, suggests that Sequence 3 best resembles a progradational sequence, that was sourced from a region to the east of the WOB.

Sequence 3 could be interpreted as is either a prograding carbonate or clastic sequence; where the moderately continuous strong amplitudes of Unit 1 could represent a carbonate platform or a clastic delta, and the weak and highly continuous amplitudes within Unit 2 could represent the more distal facies within the system, such as mudstones or marls. However, the low angle of downlap (5 - 15°) observed onto Unconformity A suggests that Sequence 3 most likely represents a clastic sequence, as opposed to a carbonate platform (e.g. Catuneanu 2006 and references therein).

Assuming that Sequence 3 does indeed represent a clastic progradational succession, the thickness of the tapering wedge implies that water depths were of the order of several hundred to 1000 metres (Fig 4.25). Such a deep marine environment is highly difficult to envisage within this region of the Atlantic margin during the Devonian to

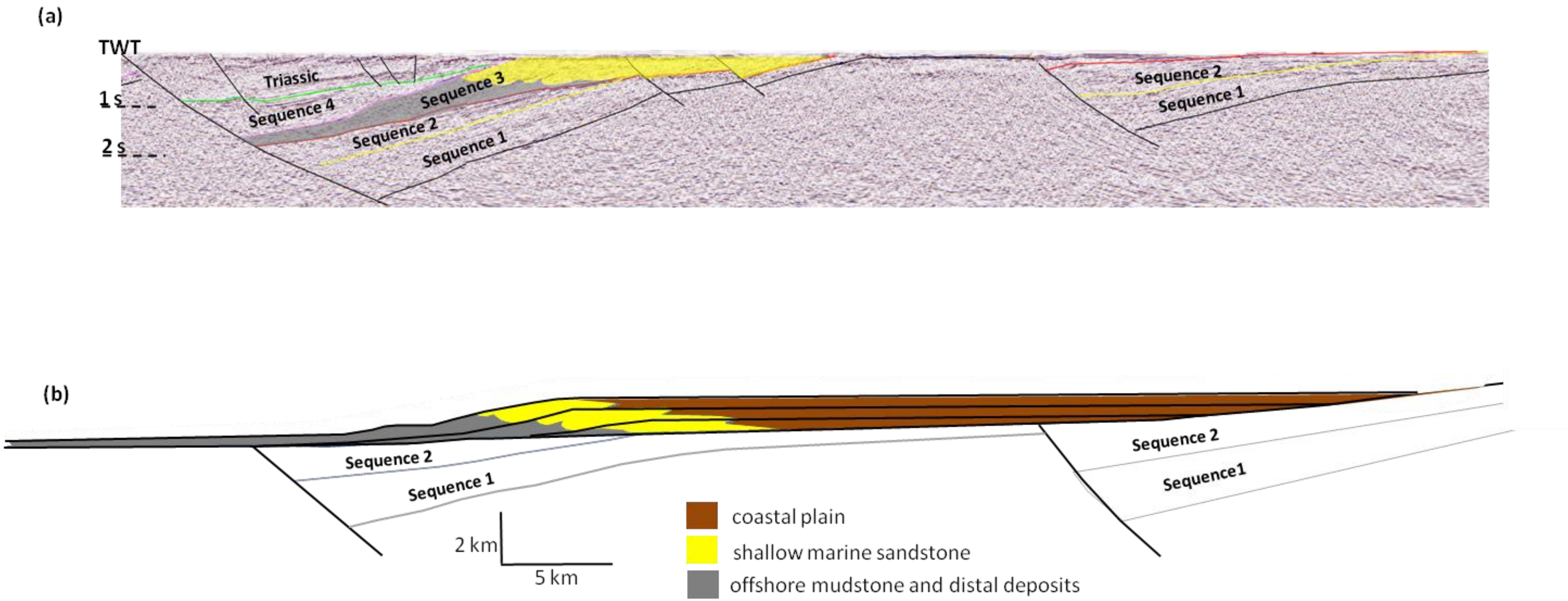


Figure 4-25. (a) Interpretation of an arbitrary line through seismic lines 1 and 2 – for location see Fig 1. (b) Structural reconstruction of the depositional geometry of Sequence 3. The depositional geometry is interpreted to represent a Late Permian (Zechstein) clastic prograding delta system that was sourced from a region to the east of the West Orkney Basin.

Carboniferous (e.g. Torsvik et al. 2002; Bruce & Stemmerik 2003), which supports the argument put forward within this study for a Late Carboniferous/Variscan age for Unconformity A, and therefore, Sequence 3 most likely post-dates the Late Carboniferous.

It is most improbable that Sequence 3 is Early Permian in age, since well penetrations of Lower Permian rocks in the basins that border the WOB (i.e. Faroe-Shetland Basin and the North Sea Basins) indicate that the Early Permian was a time of intense igneous activity, with erosion or non-deposition, that is thought to be due to changes in regional stress pattern at the end of the Variscan Orogeny (Ziegler 1990; Ritchie et al. 2011).

It seems most probable that Sequence 3 is Late Permian in age, because during the Late Permian a glacio-eustatic rise in sea level combined with southward propagation of the Arctic rift system towards western Ireland and the northern North Sea, resulting in southward marine transgression from the Artic and development of the Zechstein Sea across much of Northern Europe (Coward et al. 2003). The Zechstein Sea (Fig 4.26a) is reported to have transgressed south into the North Sea Permian Basins, via an incipient Viking Graben (Glennie et al. 2003). Whereas in the Faroe to West Orkney region, seismic profiles and well penetrations of Late Permian marine mudstones, sandstones, limestones and thick halite sequences around the northwest of the east Shetland High and in the West Orkney, Minch and Papa Basins (Ritchie et al. 2010), indicates that the Zechstein sea developed within the deeper parts of these basins, to at least as far south as the West Orkney and Minch and basins (Fig 4.26b).

Therefore, Sequence 3 was most likely deposited during Late Permian marine transgression into the West Orkney Basin, with accommodation space being created by extension on the Sula-Sgier and Outer Isles Faults (Fig 4.26b). The progradatioanl geometry of Sequence 3, from the area to the east of the West Orkney Basin, implies that sediment supply rates were high, during overall Zechstein marine transgression. Much of the region between the West Orkney Basin and incipient Viking Graben (Fig 4.26a) is believed to have been mainly a structural high throughout the Late Permian (Glennie et al. 2003). This provenance is geographically well located relative to the size and progradational geometry of Sequence 3.

The observed conformal onlap of Sequence 4 onto Sequence 3 and the westward thickening of Sequence 4 towards the Stack-Skerry (Fig 4.15 and 4.16) and Sula-Sgier Fault (Fig 4.17 and 4.20) Zones, implies a major change in sediment supply occurred during deposition of Sequence 4, in association with evaporite basin formation (Fig 4.26c). It is postulated here that the NCTZ (North Coast Transfer Zone), identified by Wilson et al. (2010), may have formed in the Late Permian during deposition of Sequence 4, in order to accommodate extension between the Minch Basin and the reactivated Stack-Skerry Fault Zone (Fig 4.26c).

The transition from the Permian to Triassic in the NE Atlantic was accompanied by continued rifting and regression of the Zechstein Sea (Coward et al. 2003). Triassic well correlations between the WOB, Solan (Herries et al. 1999) and Papa Basins (Ritchie et al. 2011) (Fig 4.1) imply that the Triassic depositional environment was dominantly fluvial and alluvial, with minor sheet flood deposits.

The Permo-Triassic wedges apparent on seismic within the WOB, Solan and Papa Basins (Fig 4.1) have been suggested to not represent separate half-graben depo-centres, but actually the erosional remnants of a single large basin, where the apparent wedge-shapes are actually superficial; being the result of major erosional

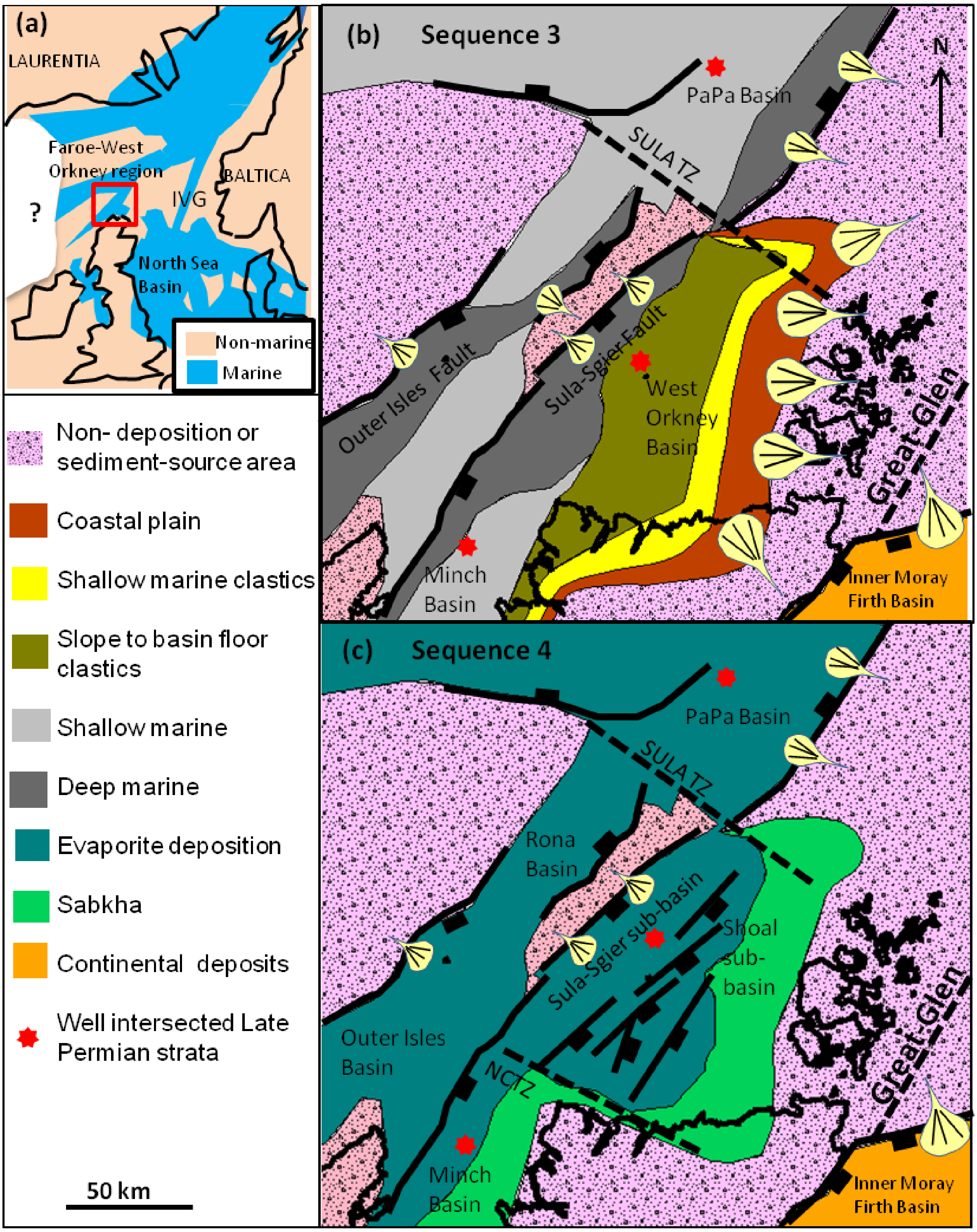


Figure 4-26. Gross depositional environmental maps. (a) Extent of Zechstein Sea – modified from Glennie et al. (2003). Red box illustrates the location of (b) Sequence 3 and (c) Sequence 4. Abbreviations – NCTZ: North Coast Transfer Zone identified by Wilson et al. (2010), Sula TZ: Sula Transfer Zone from Bird et al. (2015)

peneplanation during the Mid Jurassic (Booth et al. 1993; Herries 1999). However, the strong evidence presented in this study for Permo-Triassic rifting within the WOB is in conflict with the views expressed by these authors. Furthermore, seismic mapping within the basins to the immediate NW of the WOB (Rona, Solan and Papa Basins), during this study, has led to the recognition of seismic reflections within Permo-Triassic sequences diverging towards the West-Shetland-Spine, Rona and Solan Faults (e.g. Figs 4.27 and 4.28), therefore, implying that these faults were active during the Permo-Triassic. A major northwest-southeast transfer zone identified by Bird et al. (2015) (Sula TZ: Fig 4.26) is interpreted to have accommodated extension between these major Permo-Triassic half-graben systems (Fig 4.1 and 4.2).

An important observation made during this work, is that a considerable portion of the faulting (which has similar strikes to the major fault zones) in WOB appears to offset the interpreted Devonian and Permo-Triassic sequences with no apparent changes in stratigraphic thickness (at the scale of the seismic dataset) (e.g. Figs 4.3, 4.29 and 4.30). This could suggest that a third phase of rifting has occurred in the WOB, which post-dates the age of the preserved Devonian to Permo-Triassic sequences in the basin. However, in general, the faults that are seen to offset the Devonian to Permo-Triassic sequences (with no visible thickness changes in strata), have similar strikes and fault dips as the low angle (30° to 50°) Stack-Skerry Fault Zone, and therefore, if there was a third phase of rifting in the WOB (i.e. that post-dated major Permo-Triassic tilting of the half-grabens), then a considerable number of the faults in the basin would be expected to exhibit steeper dips (i.e. closer to 60°) – which does not appear to be the case. Nevertheless, it is difficult to completely rule out a third rift-phase having occurred in the basin, although it can be deemed insignificant when compared to the apparent magnitude of the Devonian and Permo-Triassic rift events.

4.2.3 Post-Triassic development

The Triassic-Jurassic shift in the North Atlantic region saw rifting breach Pangea, with incipient ocean-floor spreading in the proto-Central Atlantic and the Tethys, resulting in marine transgression (Coward et al. 2003). Early Jurassic rifting has been documented as far north as the Hebrides Basin (Morton 1989) and offshore mid-Norway (Blystad et al. 1995).

The only well penetration of Lower Jurassic strata in the WOB to Faroe-Shetland region is in the West Solan Basin (Fig 4.1 and 4.2), where 770 m of marginal to marine Liassic mudstones and sandstones were encountered in exploration well 202/03a-3 (Fig 4.27 and 4.28). Seismic mapping of the Liassic sequence indicates that it is only preserved within the hangingwall to the Solan Fault, which this study interprets as a Permo-Triassic rift structure (discussed previously). There does not appear to be any evidence for a Early Jurassic rift-phase. However, our understanding on the extent of Early Jurassic rifting and deposition in this region is partially hindered by a regionally extensive Mid-Jurassic uplift and erosion event (Booth et al. 1993; Dean et al. 1999) (e.g. Fig 4.28 and 4.31).

Nonetheless, the preferred model for the WOB Rona, Solan and Papa Basins in this study is that major Triassic rifting dwindled into the Lower Jurassic, giving way to post-rift subsidence and marine transgression from the southwest in association with seafloor spreading in the central Atlantic (e.g. Coward et al. 2003).

The nature, magnitude and significance of the Mid-Jurassic uplift and erosion event is not fully clear, although similar Mid Jurassic unconformities have been reported from other areas such as the North Sea, Irish Sea and the northern Porcupine and Slyne

Basins. Underhill and Partington (1993) postulated that the Mid Jurassic uplift event in the Central North Sea was due to the region being underlain by hotspot. This hotspot may have belonged to a family of hotspot related uplifts that extended across NW Europe (Dore et al. 1999).

The amount eroded at the Mid-Jurassic unconformity has been estimated to be about 1.5 km from AFTA in the Solan Basin (Booth et al. 1993). Considering the regional extent and nature of this erosional event (e.g. Dore et al. 1999), it is reasonable to infer that in the order of 1.5 km of section was also eroded from the WOB during the Mid-Jurassic.

Upper Jurassic rocks overlie the Mid-Jurassic unconformity in the Rona, West Solan and Papa Basins, and comprise a fining upwards sequence of shallow marine sands to organic-rich shales, suggesting marine transgression of the Mid-Jurassic unconformity surface (Verstralen et al. 1995). The succession is a few hundred metres thick, with minor thickness variations, and thus, Upper Jurassic rocks in the region are interpreted to have been deposited in a post-rift setting (Dean et al. 1999). It is possible that a thin sequence of Upper Jurassic rocks were deposited across the WOB, but their presence or absence is considered insignificant to this study.

Within the Rona, Solan and Papa basins, deposition of the Upper Jurassic organic shales continued across the Jurassic-Cretaceous boundary, but terminated in the Late Ryazanian to Valanginian, due to the re-oxygenation of oceanic waters and subsequent onset of major NW-SE rifting, which is broadly interpreted to have occurred in three phases: (1) Valanginian-Barremian, (2) Aptian-Albian and (3) Campanian-Maastrichtian (Booth et al. 1993; Dean et al. 1999).

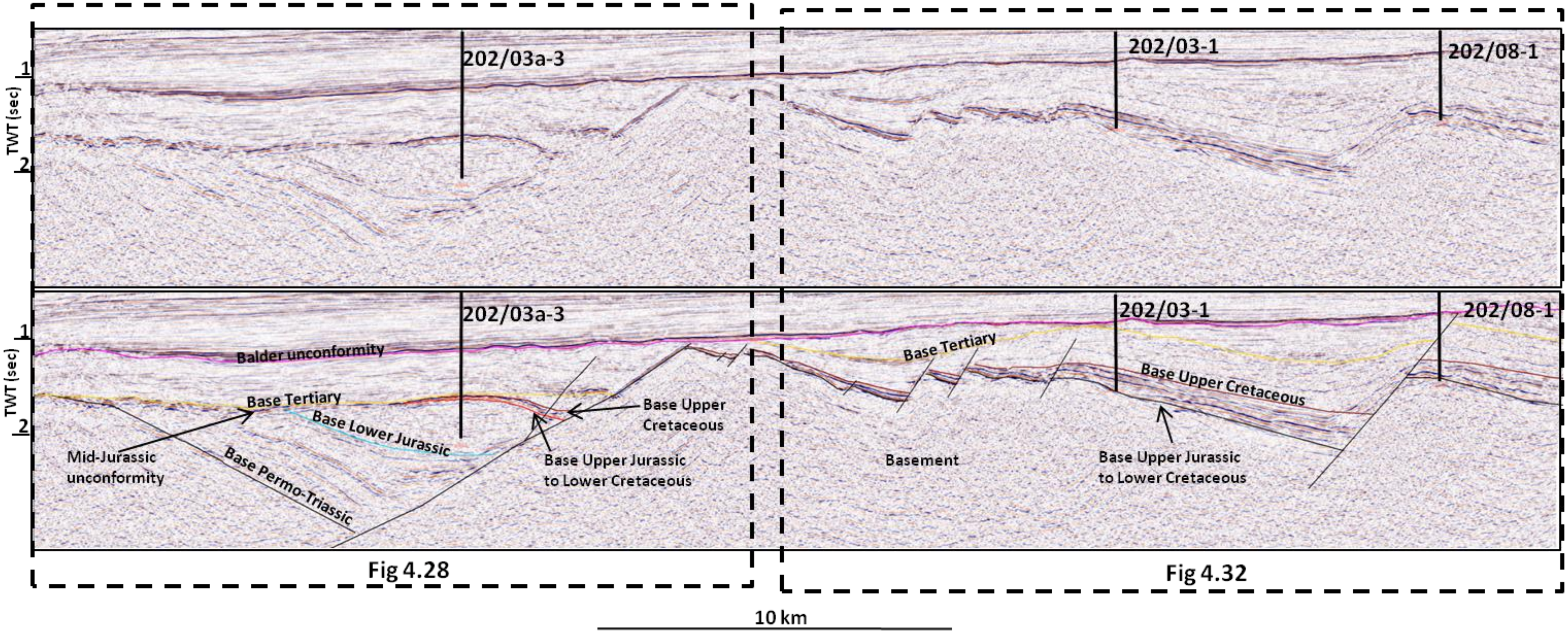


Figure 4-27. Interpretation of seismic line 11. For location see Fig 4.1 and 4.2.

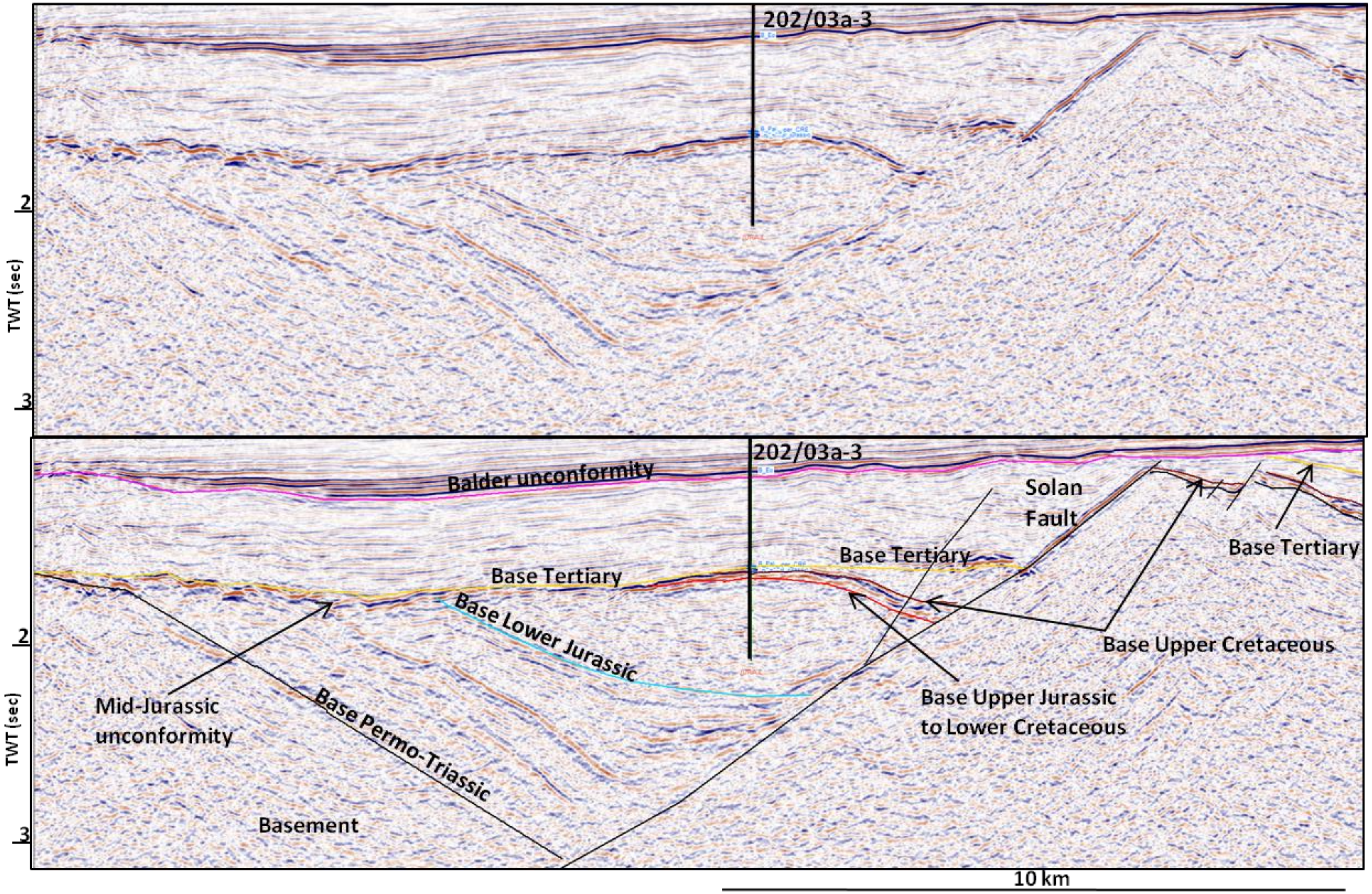


Figure 4-28. Portion of seismic line 11. For location see Fig 4.27. Note the divergence of Permo-Triassic stratigraphy towards the Solan Fault, indicating it was active during the Permo-Triassic.

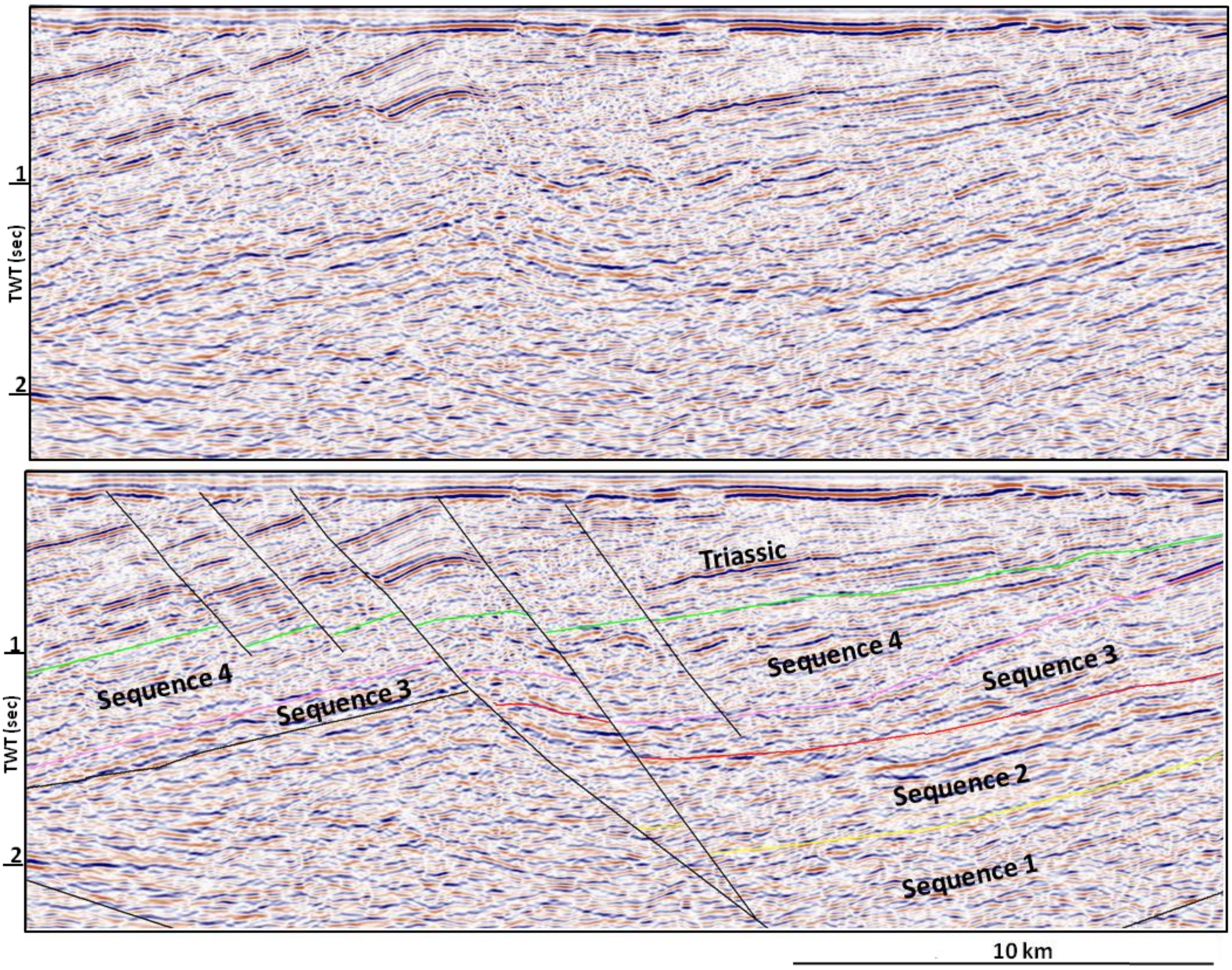


Figure 4-29. Portion of seismic line 1, showing that all observed faulting in the WOB have similar fault dips as the low angle (30° to 50°) Stack-Skerry Fault Zone and therefore most likely formed during major fault-controlled hanging-wall tilting. For location see Fig 4.3.

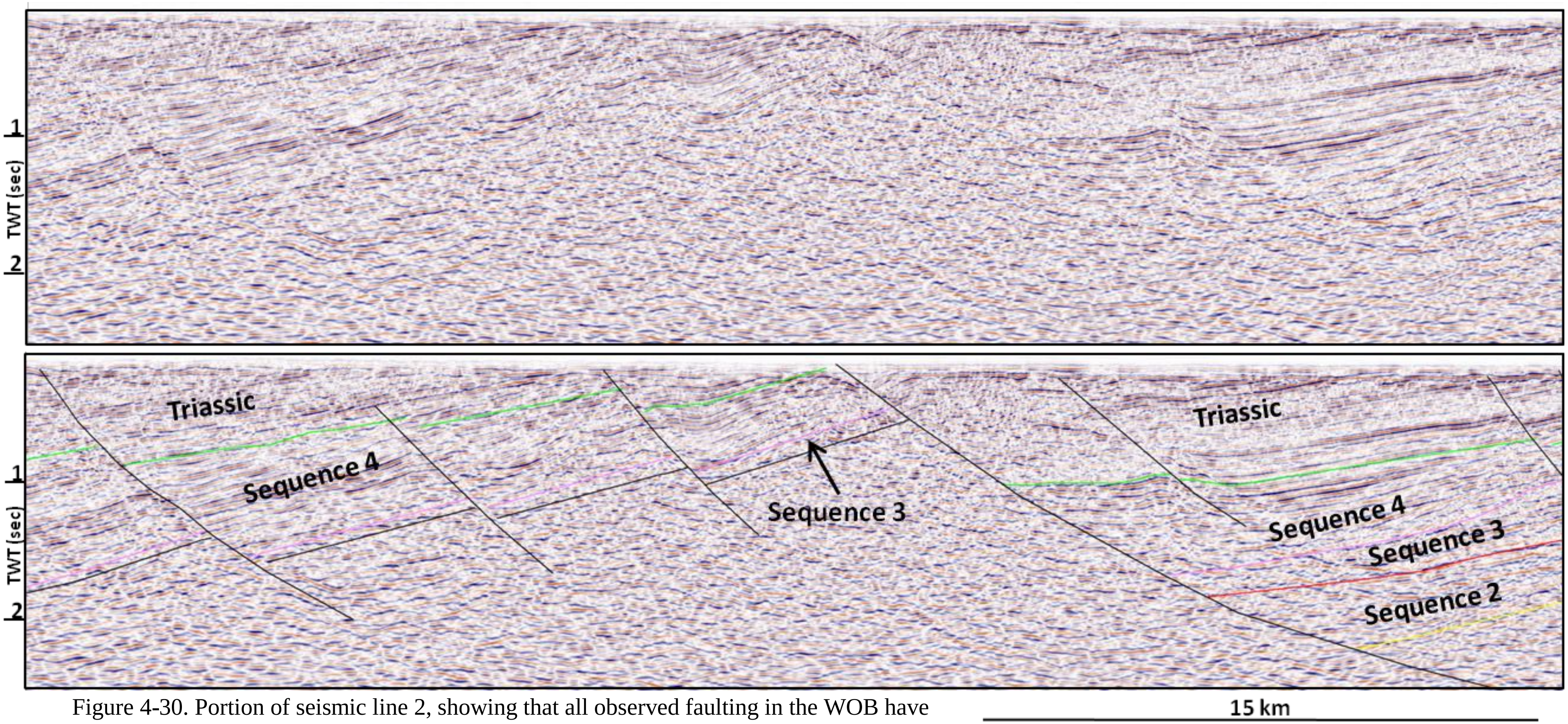


Figure 4-30. Portion of seismic line 2, showing that all observed faulting in the WOB have similar fault dips as the low angle (30° to 50°) Stack-Skerry Fault Zone and therefore most likely formed during major fault-controlled hanging-wall tilting. For location see Fig 4.3.

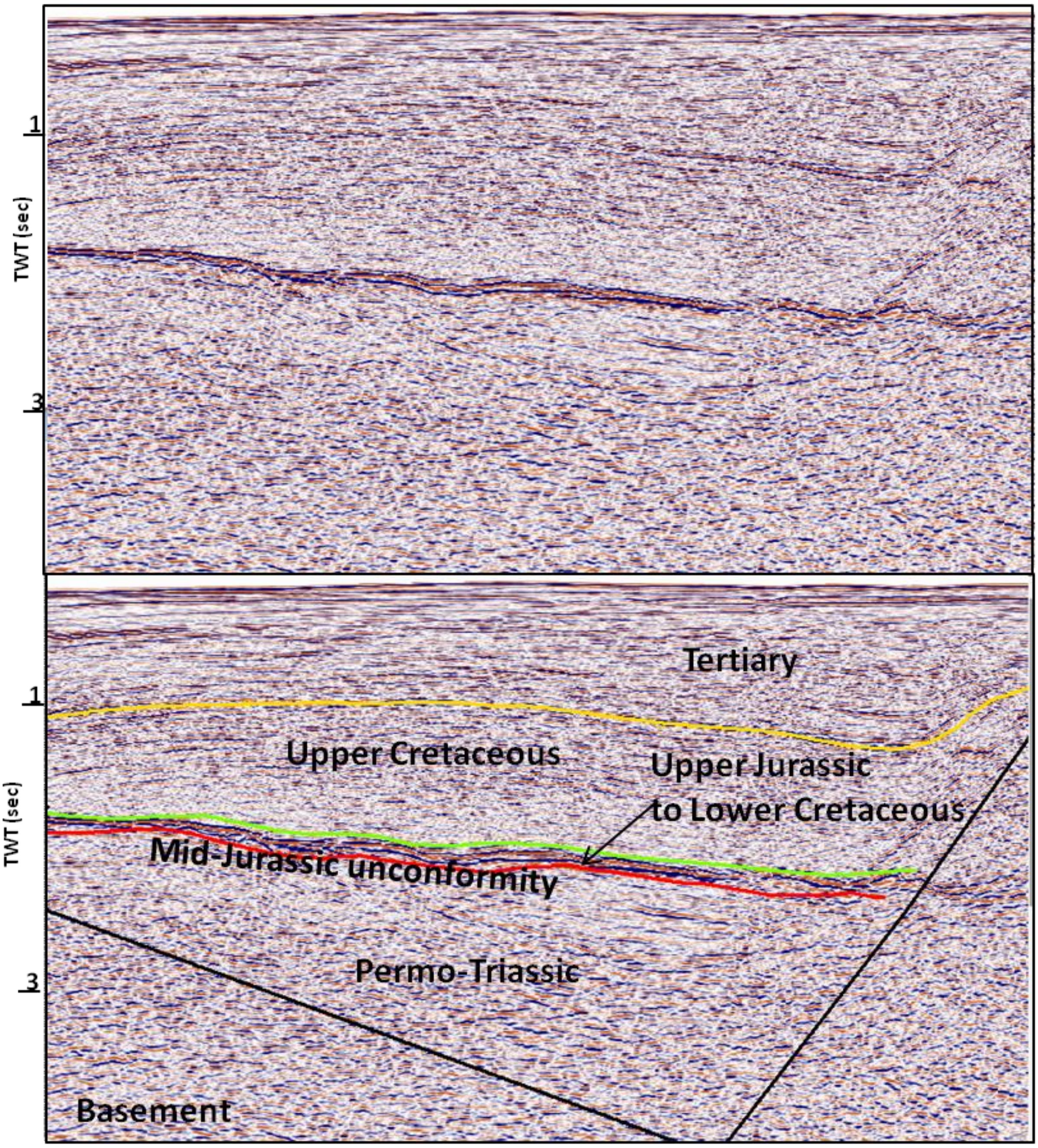


Figure 4-31. Seismic line 12. For location see Fig 4.1 and 4.3. Note the truncation of Permo-Triassic stratigraphy at the Mid-Jurassic unconformity.

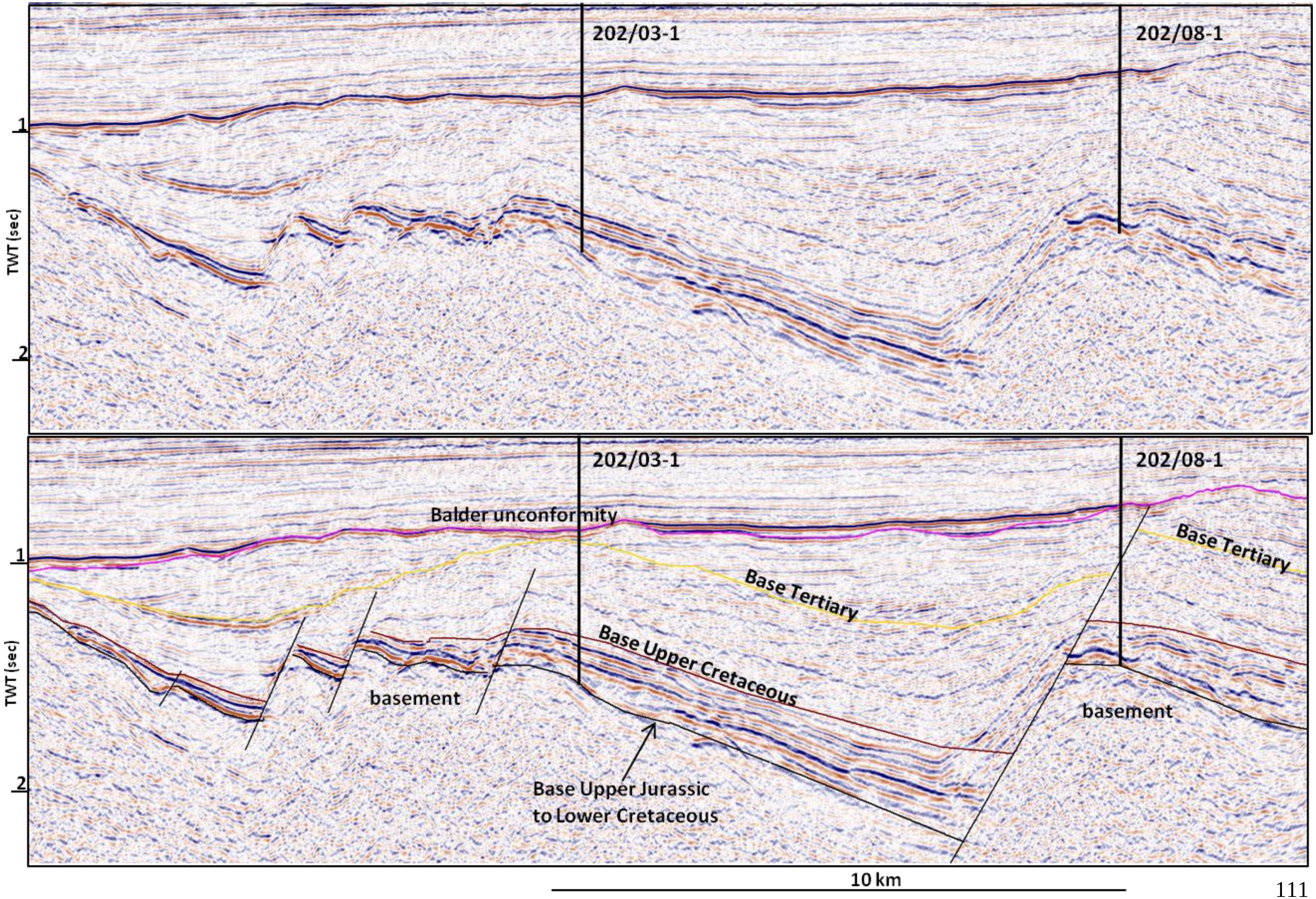


Figure 4-32. Portion of seismic line 11. For location see Fig 4.27.

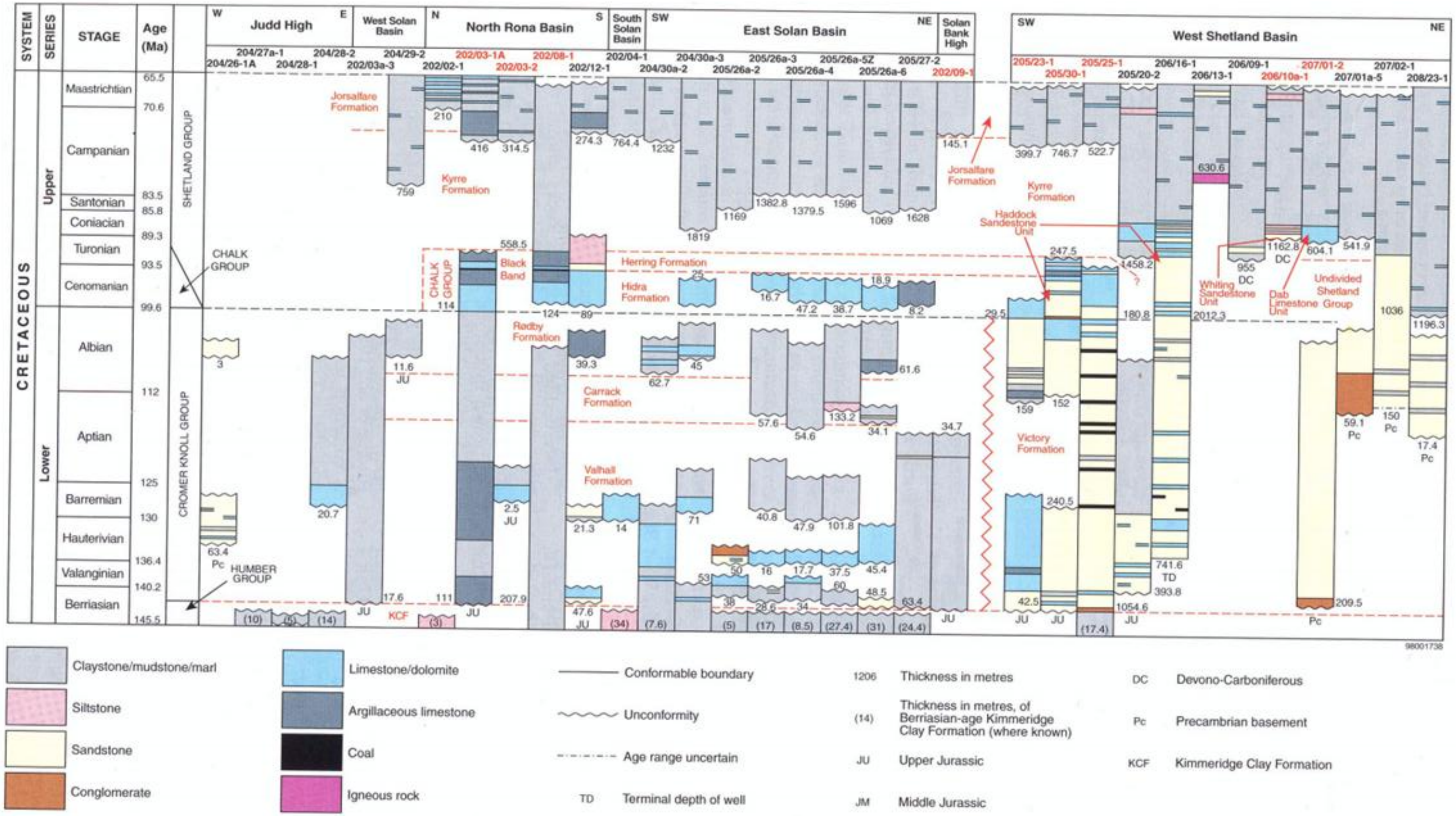


Figure 4-33. Regional Cretaceous well correlation (from Ritchie et al. 2011). Note the amount of unconformities in the Lower Cretaceous succession in the Solan and Rona Basins, which are situated immediately to the NW of the WOB. Location of wells in the Rona and Solan Basins are shown in Fig 4.2.

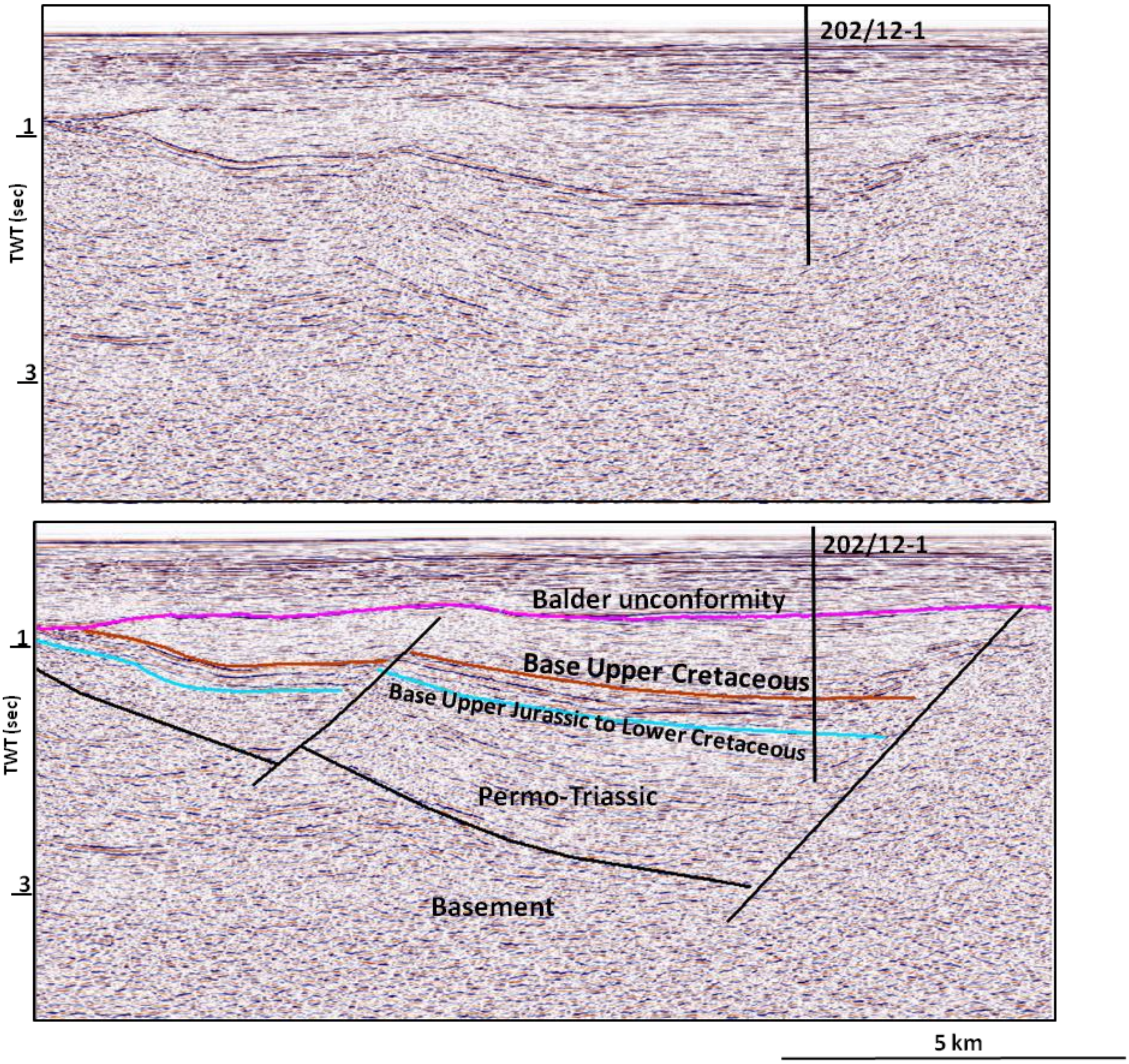


Figure 4-34. Interpretation of seismic line 13. For location see Fig 4.1 and 4.2.

Lower Cretaceous rocks in the Rona and Solan basins are a few hundred metres thick, and consequently are grouped together with Upper Jurassic rocks as a mappable seismic sequence (e.g. Fig 4.32). They consist of mainly fine grained sandstones and pelagic carbonates that are punctuated by numerous unconformities (Fig 4.33). Whereas, in the Shetland Basin, up to 1200 m of Lower Cretaceous coarse clastic sediments were deposited in the hangingwall of the Shetland Spine Fault (Fig 4.1). Results from AFTA on WOB well 202-19-1 (Fig 4.2 and 4.3) and shallow BGS boreholes within the WOB, suggest the WOB experienced a phase of uplift in the Early Cretaceous (Holford et al. 2010).

Thus, it is suggested here that the WOB experienced basin-flank uplift during Early Cretaceous rifting in the Faroe-Shetland Basin. Sub-areal exposure of the WOB during the Early Cretaceous could have provided a linked sediment-source area with the Shetland platform, for coarse clastic deposition into the Faroe-Shetland Basin.

Regional subsidence, with associated marine transgression occurred during the Late Cretaceous, resulting in deposition of hemipelagic deep marine shales with occasional limestones in the basins to the immediate NW of the WOB. The preserved Upper Cretaceous sequence in the Rona and Solan Basins is up to 1000 m thick (e.g. Fig 4.31 and 4.32).

The widespread deposition of deep marine shales and limestones within the basins immediately bordering the WOB (e.g. Solan and Rona basins), and chalks on the terraces of the Shetland Spine Fault (e.g. Booth et al. 1993) and the Shetland Platform (e.g. Larsen et al 2010), raises the likelihood that the WOB was also transgressed and buried under a thicker layer of Upper Cretaceous sediments. There is no evidence of any structural hinge between the WOB and areas of thick Late Cretaceous accumulation further to the northwest that could, as an alternative model favour differential thickness across this portion of the NE Atlantic borderland.

It has been proposed that Palaeocene rifting in the Faroe-Shetland Basin was contemporaneous with regional uplift, high heat flows and widespread erosion of the Scottish Highlands (Dean et al. 1999), which resulted from either crustal under-plating of the Icelandic hotspot (White & Lovell, 1997; Jones et al. 2002) or intra-plate compression, driven by plate boundary forces (Holford et al. 2009; Stoker et al. 2010).

A major regional Late Palaeocene erosional unconformity (Balder unconformity) has been mapped during this study, in the Rona and Solan Basins, and towards the margin of the WOB (Fig 4.27 and 4.34). Below the unconformity, the Palaeocene succession can be observed to thin northwards from the Solan Basin to the Rona Basin, where it becomes absent and consequently Upper Cretaceous rocks subcrop the Balder Unconformity (compare Fig 4.27 and Fig 4.34). This suggests that either erosion was greater towards the south or Palaeocene rocks were barely deposited in the Rona Basin and the flanks to the WOB. The latter seems most probable, and would therefore indicate that the WOB was a sub-aerial source area during the Palaeocene, for north-westward directed Palaeocene deposition into the Faroe-Shetland Basin.

Throughout the remainder of the Cenozoic, this region of the NE Atlantic experienced continued pulses of uplift, associated with igneous underplating and North Atlantic sea floor spreading (Coward et al. 2003). The West Shetland Shelf (Stoker et al. 2010) and probably the WOB continued to be a sub-areal sediment-source area for Tertiary deposition into the Faroe-Shetland basins during the Cenozoic. Holford et al. (2010)

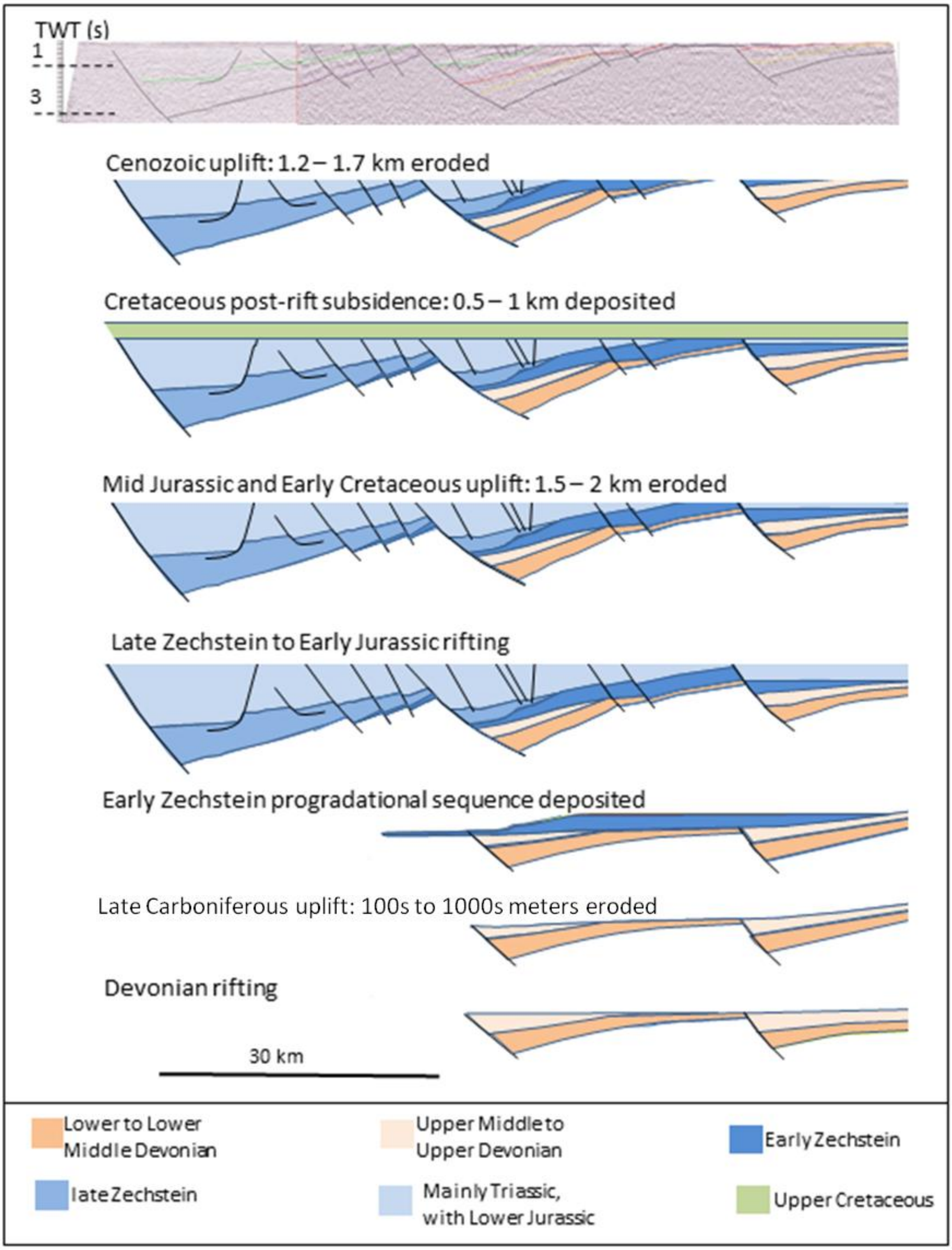


Figure 4-35. Schematic tectono-straigraphic evolution model for WOB, which is based on structural reconstruction of a time seismic section.

estimated from AFTA that 1.2 to 1.7 km of section was removed from the WOB during Cenozoic uplift.

In summary, there is good evidence that the WOB experienced three post-Triassic uplift events in the Mid-Jurassic, Early Cretaceous and Cenozoic; as illustrated by the schematic tectono-stratigraphic evolutionary model in figure 4.35. Mid-Jurassic uplift and erosion of the basins that border the WOB is well observed, where removal of 1.5 km of section has been estimated from AFTA (e.g. Booth et al. 1993), and thus it is conceivable that a similar order of magnitude was also eroded from the WOB during the Mid-Jurassic. Rift-flank uplift and erosion of the WOB probably occurred during the Early Cretaceous, in association with significant Early Cretaceous rifting in the Faroe-Shetland Basin. Late Jurassic transgression and deposition was most likely insignificant, and therefore it is plausible to model the WOB as experiencing a net-uplift event from the Mid-Jurassic to Early Cretaceous, with removal of about 1.5 to 2 km of section. The WOB was exhumed throughout the Cenozoic, with removal of about 1.2 to 1.7 km of section (e.g. Holford et al. 2010).

Thus, the present-day net-thickness (for Mid-Jurassic to Early Cretaceous and Cenozoic exhumation) of removed section is estimated to be about 2.7 to 3.7 km. It is conceivable that 0.5 to 1 km of sediments were deposited across the WOB during regional subsidence in the Late Cretaceous. This suggests that about 2 to 3 km of Triassic to Early Jurassic sediments have been eroded from the WOB.

4.3 Conclusion

(1) A regional angular unconformity (Unconformity A) bounding the top of a syn-rift sequence was identified within the WOB and can possibly be related to Late Carboniferous inversion of the Great-Glen Wall-Boundary Fault system.

(2) Two characteristic syn-rift sequences are distinguishable below Unconformity A, which are proposed to represent the offshore continuation of the Lower to Lower Middle Devonian and Upper Middle to Upper Devonian successions. The Stack-Skerry Fault Zone is interpreted to be the western tectonic boundary the Orcadian Basin.

(3) A characteristic sequence (Sequence 3) that down-laps onto Unconformity A and thickens eastward, is interpreted to represent a Late Permian progradational delta-system.

(4) A second major phase of rifting, in association with evaporite basin formation (deposition of Sequence 4), and formation of new faults and reactivation of pre-existing Devonian faults, is interpreted to have initiated in the Late Permian and dwindled into the Early Jurassic.

(5) The present-day net-thickness (for Mid-Jurassic to Early Cretaceous and Cenozoic exhumation) of removed section is estimated to be about 2.7 to 3.7 km. It is conceivable that 0.5 to 1 km of sediments were deposited across the WOB during regional subsidence in the Late Cretaceous. This suggests that about 2 to 3 km of Triassic to Early Jurassic sediments have been eroded from the WOB.

Chapter 5

5 Play Fairway Analysis

5.1 Introduction

The WOB is considered to have the potential to host a working petroleum system, based on the occurrence of mature Devonian lacustrine source-rocks that outcrop in the onshore portions (Orkney and Caithness) of the WOB (e.g. Marshal et al. 1985; Hillier & Marshall 1992). However, it is entirely unknown if a viable petroleum play exists offshore, or even if there is potential for entrapment and preservation of hydrocarbons, due to trap and charge timing issues.

There is a significant lack of understanding on how Devonian lakes were inter-connected across the Orcadian Basin rift-system, and thus how source-rock is distributed between half-graben systems. For example, did the lacustrine sedimentation, 750 m thick on Orkney, surround or pass over local basement footwall highs in the WOB? Can hydrocarbons migrate around these barriers or is the WOB limited to sub-basins?

Two themes have dominated models of sedimentation in continental rifts. Both climate and structure have been claimed to be the single most important control on sedimentary facies distribution within continental rift-systems (Lambiase & Bosworth 1995). Olsen (1986) has suggested that periodically fluctuating climate controls vertical variations in sedimentary facies in Mesozoic rift basins of the eastern USA. Similarly, Frostick & Reid (1989) have concluded that climate is the most important control on sedimentation in East Africa today. Alternatively, other authors have proposed that structure is equally important in East Africa (Frostick & Reid 1990; Morley et al. 1990; Tiercelin 1990), and others have proposed models illustrating this control (e.g. Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000; Trudgill 2002).

In order to assess the hydrocarbon prospectivity in the WOB, a play fairway analysis approach (e.g. Fraser & Gawthorpe 1990; Fraser 2010) is conducted in this chapter. The tectono-stratigraphic development of the WOB, described in the previous two chapters, provides a fundamental background and framework for evaluating a potential petroleum system, by identifying hydrocarbon plays and characterising the key elements of a play. A play is a concept or model of how a producible reservoir and a seal facies, which together with petroleum charge system and a trap, may combine to produce hydrocarbon accumulations at a particular stratigraphic level (Magoon & Dow 1994). The geographical extent of a which a play is perceived to extend is the play fairway and is determined initially by the depositional and erosional limits of reservoir facies, but may also be limited by the known absence of any of the other factors, such as the regional extent of a hydrocarbon source-rock system or particular structural style (Alan & Alan 2005).

Play fairway analysis is essentially an assessment of exploration risk at a basin scale. In the past, the petroleum industry has applied the concept of risk mainly at a prospect-specific level. On a larger scale, analysis of the play fairway in frontier basins, such as the WOB, allows for channelling exploration effort into the most prospective parts of the basin (e.g. Fraser 2010).

5.2 Source rock

5.2.1 Nature of source rock onshore

The source-rock potential of the onshore portion of the WOB is restricted to the occurrence of organic-rich intervals within the Lower Middle Devonian lacustrine sequence (Stromness Flagstone Group) (Fig 5.1 and 5.2) (Marshall & Hewett 2003).

The lacustrine sequence comprises a series (Fig 5.2) of monotonous cycles (Crampton & Carruthers 1914) that alternate between deep lake and playa-lake environments (Mykura 1976). On Orkney, the Lower Middle Devonian comprises 87 cycles (Stromness Flagstone Group). Individual cycles range from 5 to 20 m thick and are climatic in origin; representing an alteration of dry and wet conditions in the basin (Hamilton & Trewin 1988).

Lower Middle Devonian lacustrine rocks are widespread, occupying the majority of outcropping Devonian rocks in the onshore WOB. Astin (1990) carried out detailed field mapping of Orkney and proposed that the sequence is 700 to 900 m thick on Orkney. Within Caithness, Donovan et al. (1974) estimated the sequence to be 4 km thick. However, due to the difficulty in mapping the cyclic nature of the sequence across faults, the thickness of 4 km in Caithness is likely an over estimation (Trewin 2002).

The succession consists of a cyclic alternation of thin beds of dark, laminated and non-laminated siltstones, and sandstones, which represent the deposits of a large lake system that for the majority of time was desiccated with epithermal lake development. The non-laminated siltstones and sandstone beds represent times of desiccation (Rogers & Astin 1991). They contain characteristic features such as gypsum pseudomorphs (Fig 5.3a) and sand-filled polygonal mud cracks (Fig 5.3b), which imply repeated sub-aerial exposure (Astin 1990). During these drier periods, alluvial fan systems could propagate into the basin, forming terminal fans of low relief that were dominated by sheet-floods. These deposits comprise fine-grained sandstones that are usually ripple-laminated (5.4a). The sandstone beds are generally up to 1 m thick (Fig 5.4b) and tens of metres in lateral extent. They were deposited in shallow unconfined river channels.

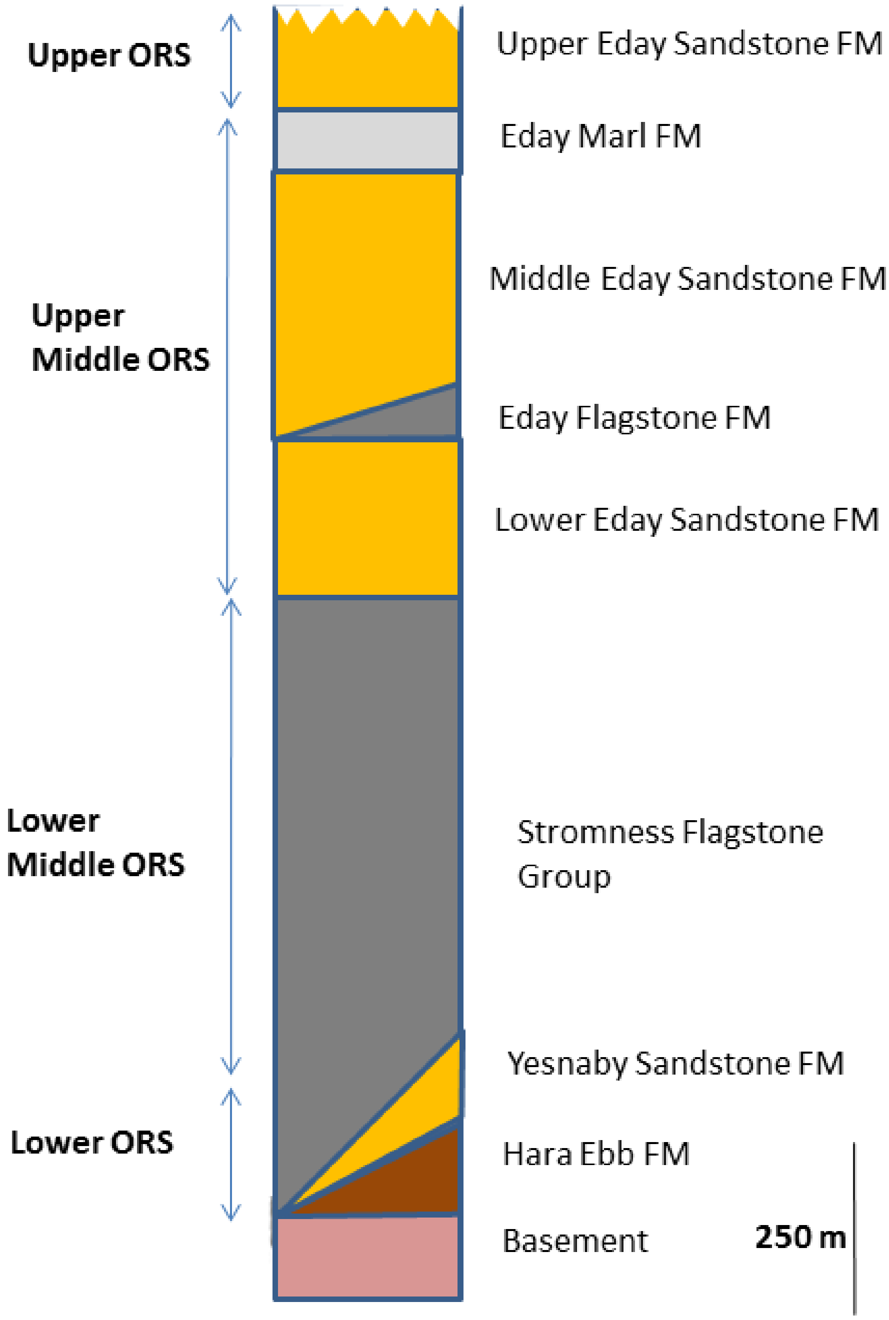
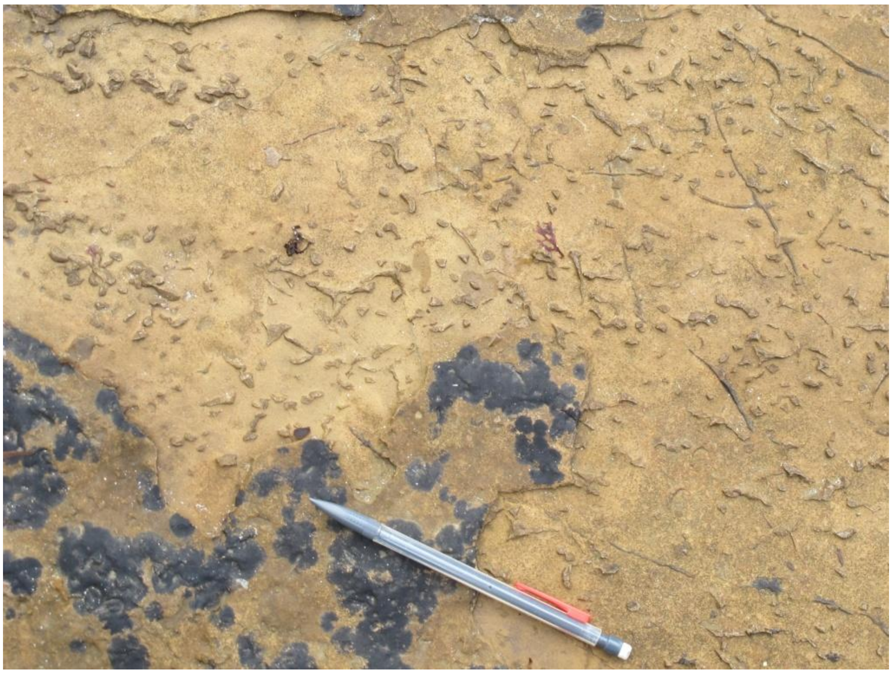


Figure 5-1. Stratigraphic column for Orkney. Based on work from Astin (1990). The source-rock interval is the Lower Middle ORS lacustrine sequence. Reservoir potential is best in the Upper Middle ORS.

Figure 5-2. GR: X323639, Y1008254 – looking NE. Outcrop picture of the Lower Middle Devonian lacustrine sequence (Stromness Flagstone Formation). The sequence consists as a series of monotous cycles that alternate between beds of deep lake to playa-lake environments.

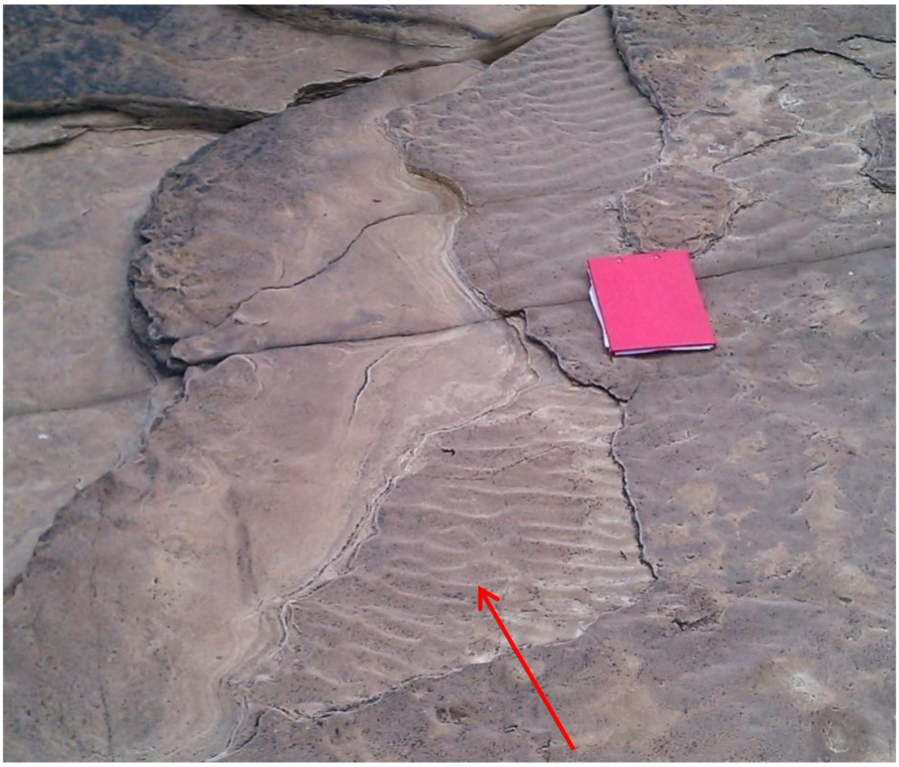
(a)



(b)

Figure 5-3. Outcrop picture of (a) (GR: X323707, Y1008179 – looking east) gypsum pseudomorphs and (b) (GR: Y323755, Y1008136 – looking east) sand-filled polygonal mud-cracks within the Lower Middle Devonian lacustrine sequence. These structures formed during drier periods when the system was desiccated.

(a)



Ripple currents

(b)

Fluvial channel

Figure 5-4. Outcrop picture of (a) (GR: X324395, Y:1028184) ripple currents and (b) (GR: X324479, Y1028159) channelized fluvial sandstone channels within the Lower Middle Devonian lacustrine succession.

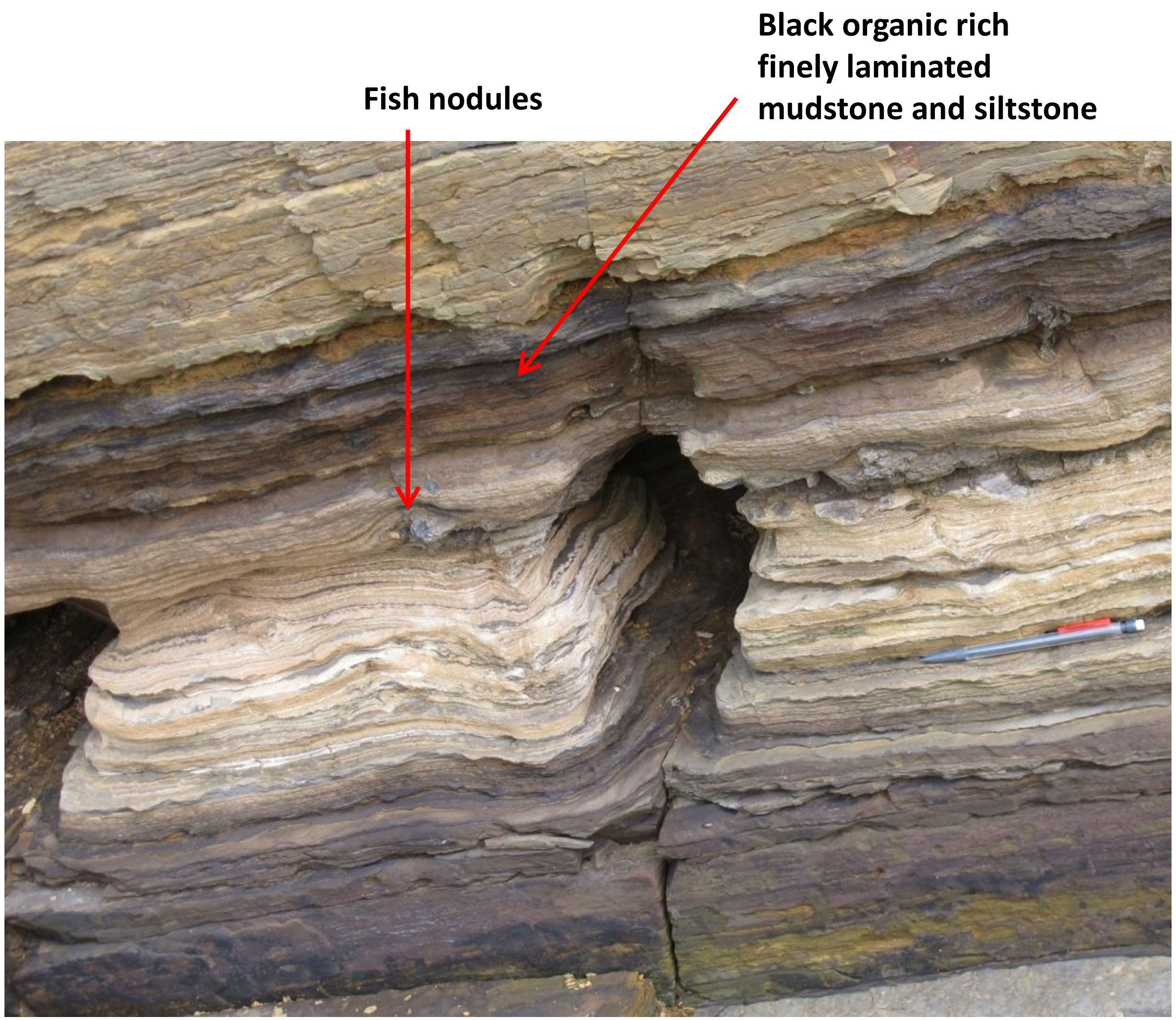


Figure 5-5. GR: X323432, Y:1008825 - looking east. Outcrop picture of organic laminated beds within the Lower Middle Devonian lacustrine sequence. Laminated facies is generally 0.5 to 2 m thick within individual cycles, and characterised by fine laminations (one to two millimetres thick) of black mudstone and siltstone that represent when the lake was at its deepest. The black nodules are fossilized fish.

For a minority of the time, the Orcadian Basin was occupied by ‘permanent lakes’, typically for a few thousand years at a time, which is represented by characteristic fine laminations (one to two millimetres thick) of black mudstone and siltstone (Fig 5.5), that are generally 0.5 to 2m thick within individual cycles. The laminations formed in thermally stratified eutrophic lakes, not affected by surface wave action (e.g. Rogers & Astin 1991). There are abundant excellent fossilized fish within the laminations. These can be seen in both plan view and cross section (e.g. Fig 5.5: black nodules). The laminate deposition is interpreted to be controlled by a seasonal climate giving deposition of annual clastic/carbonate/organic triplets on a sub-mm scale (Rayner 1963; Donovan 1980). Clastic laminae could possible represent dust storms (Trewin 1986) and fluvial activity during a rainy season. Carbonate laminae were deposited in a dry, warm season due to photosynthetic activity of phytoplankton in the lake. The organic laminae represent the annual decay of the photoplankton (Trewin 2002).

Source rock potential of the Lower Middle Devonian succession is restricted to the laminated mudstones and siltstone intervals (Fig 5.5) (Marshall & Hewett 2003). Rogers & Astin (1991) recorded these laminates to only comprise 1-16 % (average 7%) of the total outcropping lacustrine facies in the onshore area of the Moray Firth. Kelly (1992) reported similar proportions in offshore wells, where high gamma-ray log spikes associated with the radioactive fish-bed laminates comprise 14% of the lacustrine sequence.

A detailed analysis of lacustrine cycles on Orkney carried out by Speed (1999) revealed that organic rich facies have an overall average low TOC of 0.83% and comprise about 33% of the total lacustrine cycle, and that values of over 1% make up only 6% of the entire lacustrine section. However, Marshall (1998) emphasised that recorded TOC values are depressed due to organic-carbon loss during burial and maturation, as present day vitrinite reflectance values for outcrops on Orkney are between 0.7 and 1.2 VR (Hillier & Marshall 1992).

5.2.2 Source rock presence offshore

One of the primary aims in the previous chapter was to provide evidence for the presence of the Lower Middle Devonian succession in the offshore portion of the WOB. This was achieved by the recognition of two syn-rift sequences (Sequences 1 and 2) overlying basement, which comprise contrasting seismic facies characteristics, that correlate to the onshore Lower to Lower Middle and Upper Middle to Upper Devonian respectively (refer to section 4.2.1 for detailed discussion). Nonetheless, there still remains major uncertainty in the distribution of lake (source rock) and alluvial sediments within Sequence L-LM_ORS. Therefore, in this section, an attempt is made to try and reduce some of this uncertainty.

5.2.2.1 Depositional drainage pattern

Orcadian Basin rift topography and its effect on lake size and distribution across the rift system is very poorly understood (e.g. Rogers & Astin 1991). The structural controls on Lower Middle Devonian deposition in the WOB can be evaluated with seismic data (e.g. Fig 5.6 and 5.7). For example, inferred structural projection of Sequence L-LM_ORS across the central region of the Shoal High (Fig 5.7: Line A) indicates that deposition occurred across central area of the Shoal High. Whereas, to the north and south, there are regions where L-LM_ORS deposition does not appear to have occurred on the Shoal High (Fig 5.6 and Fig 5.7: Line B). The inferred structural projection of Sequence L-LM_ORS was not conducted on depth converted seismic sections (Fig 5.7), because of the large uncertainty in interval velocities throughout the geological section, and therefore depth conversion would not improve the generalised interpretation in figure 5.7.

The regions of deposition and non-deposition along the Shoal High (Figs 5.6 and 5.7), as indicated by the seismic (e.g. Fig 5.7), can be integrated with onshore paleocurrent data obtained from Orkney during this study and previous studies (Astin 1990 and Trewin 2002), in order to evaluate possible offshore structural controls in sedimentary deposition. The paleocurrent data was collected throughout the outcropping Lower Middle Devonian sequence, from NW and SW Orkney (locations shown in Fig 5.6).

Paleocurrent measurements were made from ripple currents within sheet flood and channelized sands (e.g. Fig 5.4). It is not possible to collect paleocurrent readings from a single stratigraphic interval across Orkney. As a result, only synoptic interpretations of the Lower Middle Devonian depositional environment can be made in this study. The paleocurrent data is illustrated on the rose diagrams in figure 5.8.

Rose diagrams A and B were constructed from 22 (from NW Orkney) and 19 (from SW Orkney) data-points respectively. Rose diagram A indicates that in northwest Orkney, paleocurrent flow is mainly towards the S – SSW, but with also minor flows towards the ESE. Whereas, rose diagram B illustrates that in the SW of Orkney, the majority of paleocurrent readings have a direction of flow between 40° and 70°.

The segmentation of continental rift systems has a critical influence on sedimentary deposition in basins (e.g. Leeder & Gawthorpe 1987; Gawthorpe & Hurst 1993; Eliet & Gawthorpe 1995; Gawthorpe & Leeder 2000; Trudgill 2002). The present day structural configuration of the Shoal Fault Zone is interpreted to be similar to its structural arrangement at the end of Devonian rifting (refer to section 4.2) and therefore a direct comparison can be made between the structural architecture of the Shoal Fault Zone and the onshore paleocurrent data, in order to assess possible structural controls on sedimentation (e.g. Fig 5.6).

Figure 5.6 illustrates that the Shoal High acted as a partial barrier to sedimentary drainage. The paleocurrent flow directions indicate a dominance of axial flow towards the south, with minor flows towards the ESE. This suggests that a tectonic-high or depositional barrier was located to the northwest of Orkney, around which a series of alluvial fans propagated. This interpretation is also supported by the observation that outcropping fluvial sand bodies in NW Orkney are occasionally conglomeratic, containing poorly sorted angular pebbles of psammite, quartzite and granite (e.g. Astin 1990), which could have been sourced from exposed areas of basement along the Shoal High. Paleocurrent flows towards the ESE and NE appear to correspond with relay zones within the Shoal High. Therefore, such structures could have provided access routes for the main channel systems for alluvial fan deposition into the Shoal sub-basin and the Orkney region of the WOB.

Thus, the integration of seismic and paleocurrent data (e.g. Figs 5.6, 5.7 and 5.8), indicates that in the WOB region of the Orcadian Basin, rift topography had a major control on Lower Middle Devonian depositional drainage patterns and which can be characterised as axial through-going drainage (e.g. Leeder & Gawthorpe 1987). This is similar to other continental depositional models proposed for similar settings such as Greece (Collier & Gawthorpe 1995) and Karoo rift basins of Zambia (e.g. Banks et al. 1995) and conceptual models for continental rift basins (e.g. Fig 5.9: Gawthorpe & Leeder 2000).

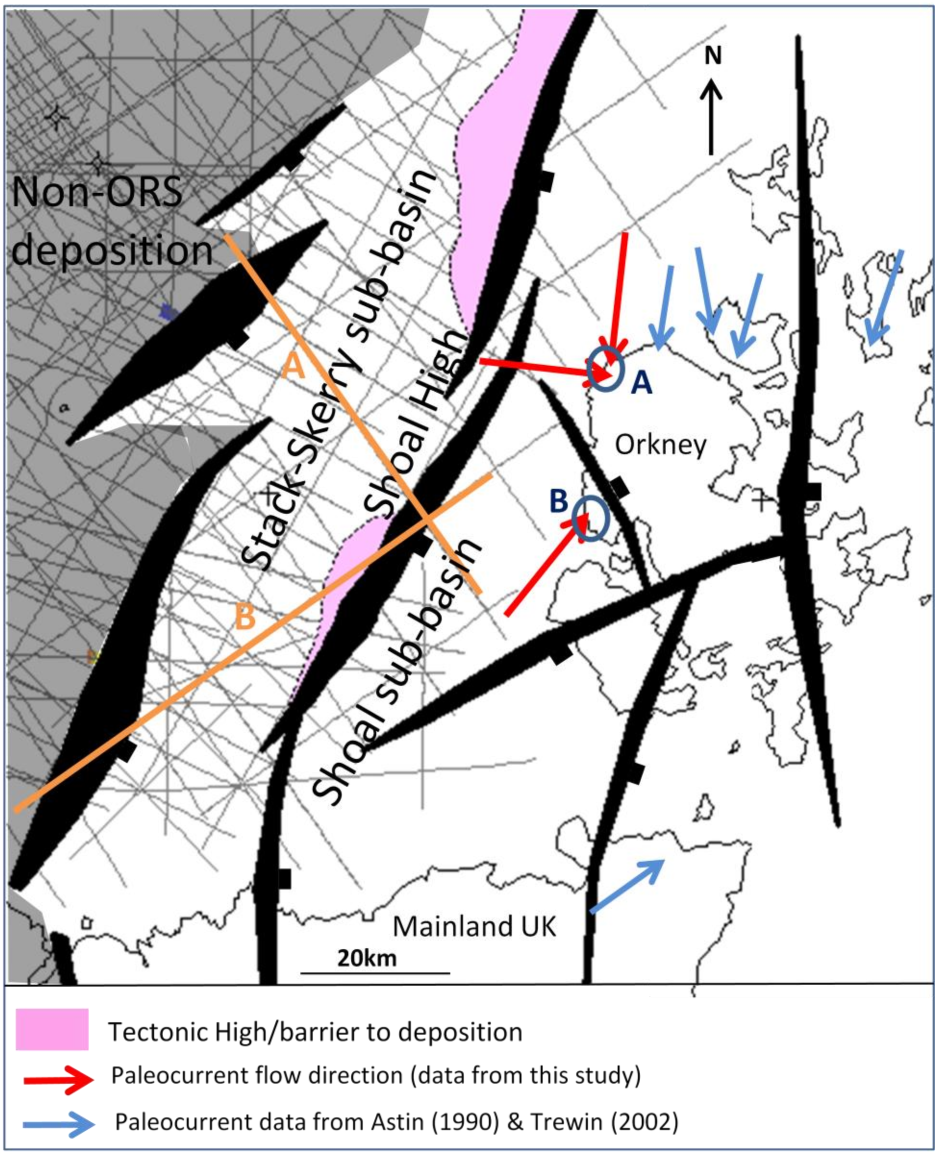
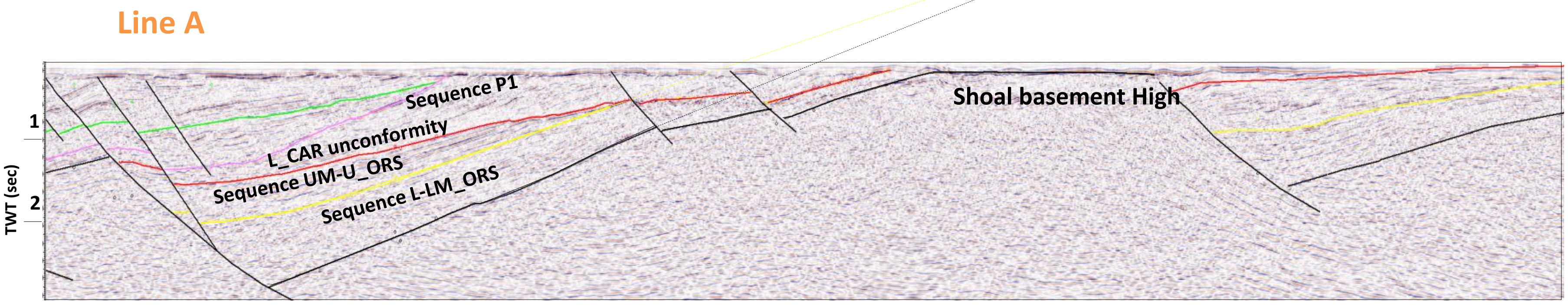


Figure 5-6. Interpretation of structural elements that controlled deposition of Sequence L-LM_ORS in the WOB, which is based mainly on seismic interpretation. Paleocurrent data obtained (during this study) from NW Orkney and SW Orkney is also shown on the map. Integration of offshore seismic interpretation and onshore paleocurrent data suggests that the Shoal High acted as a partial barrier to deposition. The observed depositional drainage pattern can be characterised as axial through-going drainage. Relay zones appear to have provided axis routes for the main alluvial fan channel systems. Locations of seismic lines in Fig 5.7 are also shown.



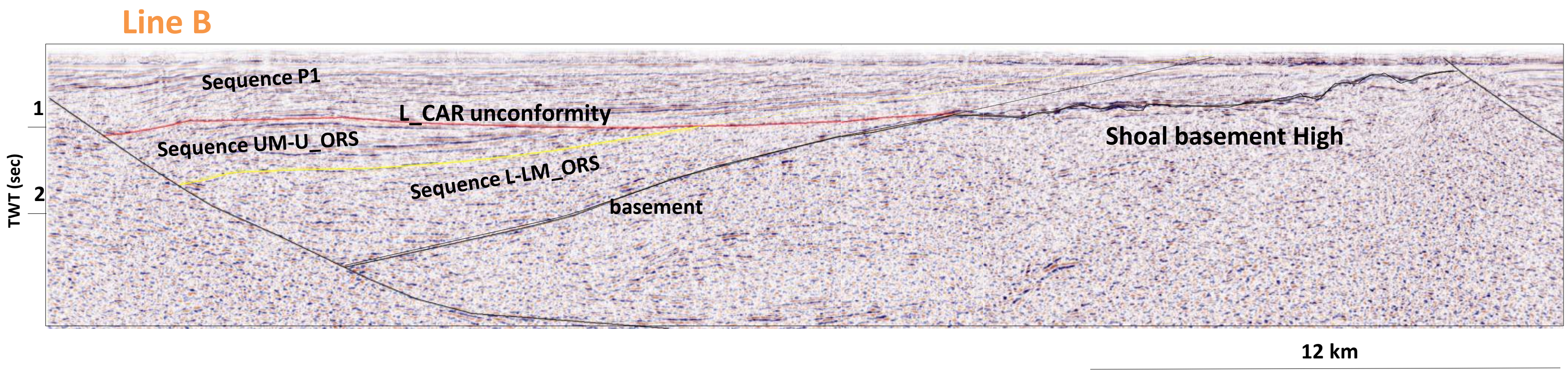


Figure 5-7. Structural projection of the L-LM_ORS Sequence across the Shoal High. Line A suggests that deposition occurred across the central region of the Shoal High, whereas Line B indicates that deposition did not occur across a region in the south of the Shoal High. Inferred structural projection was not conducted on depth sections, because of the large uncertainty in interval velocities. Refer to Fig 5.6 for locations of seismic lines and areas of non-deposition and deposition.

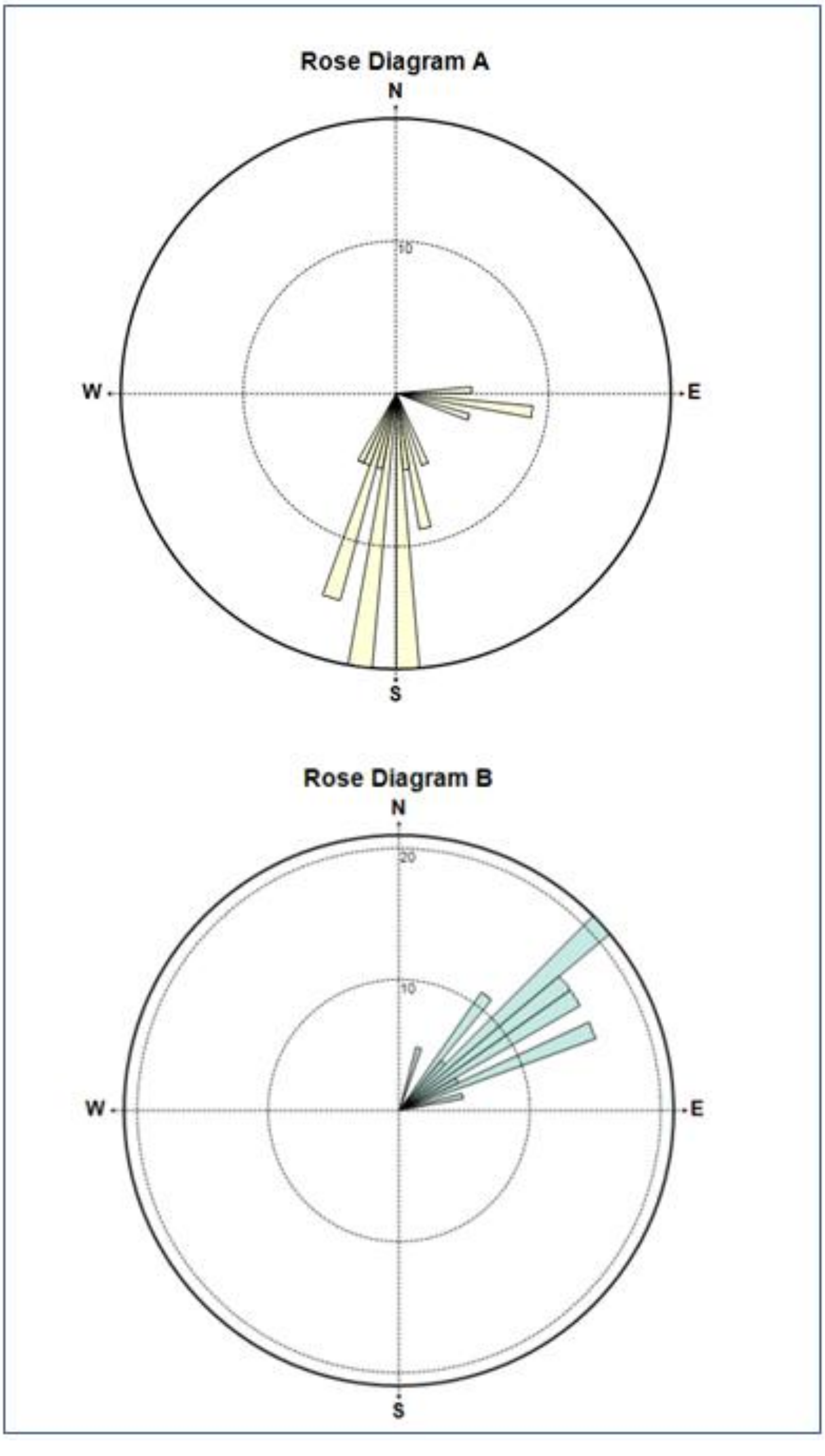


Figure 5-8. Lower Middle Devonian paleocurrent data obtained during this study from NW Orkney (rose diagram A – 22 data points) and SW Orkney (rose diagram B – 19 data points). Rose diagram A indicates that in northwest Orkney, paleocurrent flow is mainly towards the S – SSW, but with also minor flows towards the ESE. Whereas, rose diagram B illustrates that in the SW of Orkney, the majority of paleocurrent readings have a direction of flow between 40° and 70°. Paleocurrent flow directions and locations of where data was recorded is shown in Fig 5.6.

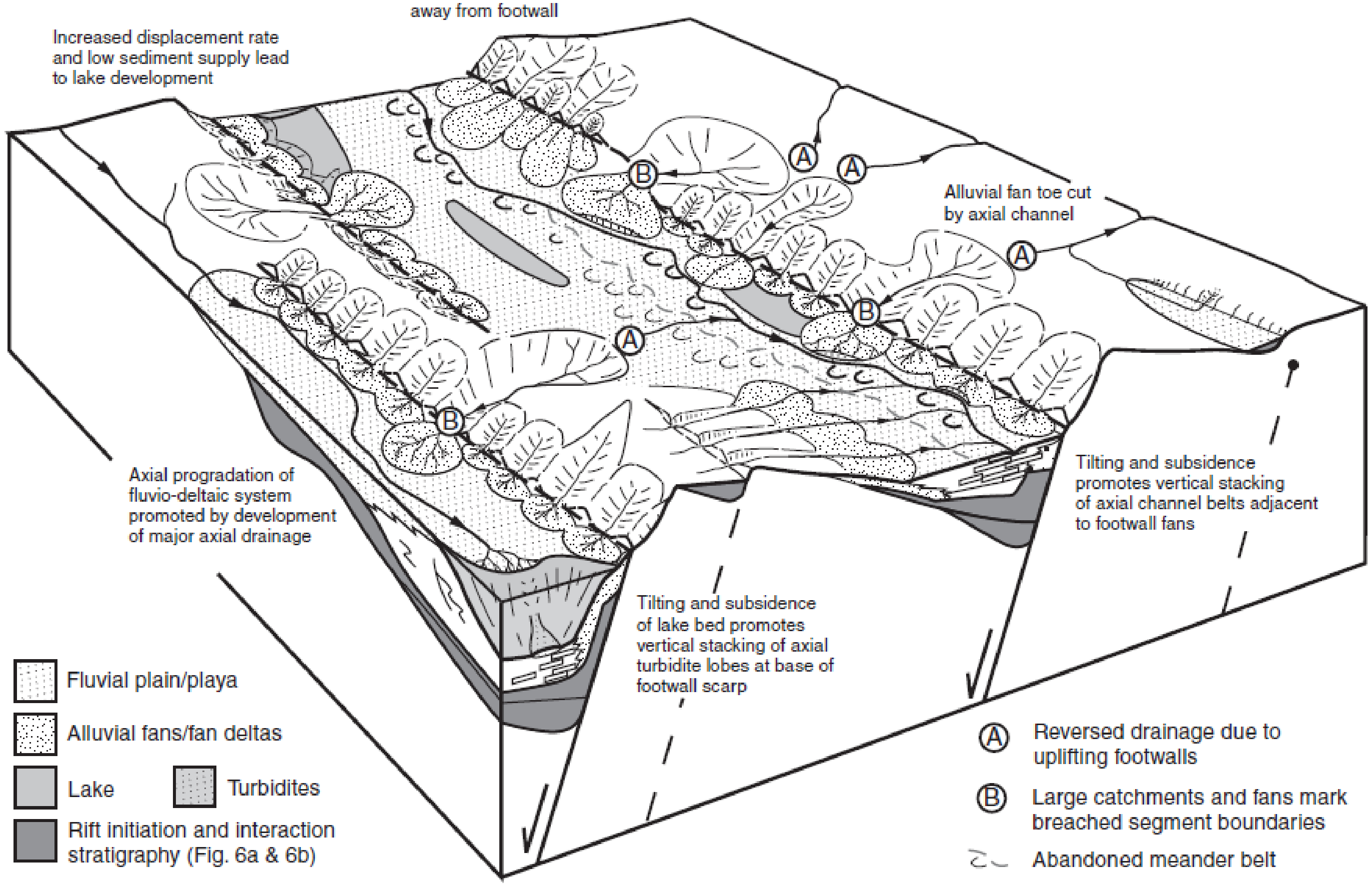


Figure 5-9. Generalised tectono-sedimentary evolutionary model from Gawthorpe & Leeder (2000) of a normal fault array (continental environments); through-going fault stage. The model is comparable to the drainage pattern characterised for Lower Middle Devonian in the WOB (e.g. Fig 5.6). The model here shows linkage of adjacent fault segments creates major linked fault zones defining half graben basins. Displacement on linked faults reduces topography of former intra-basin highs, allowing axial river to flow between former isolated basin segments. Localization of displacement causes increased displacement rates on active faults leading to the development of pronounced footwall topography and reversed antecedent drainage.

5.2.2.2 Seismic facies mapping

Sequences L-LM_ORS and UM-U_ORS (described in detail in section 4.2.1) can be sub-divided by the recognition of a distinct seismic facies unit (Unit A), comprising chaotic and structureless amplitudes, that both Sequences L-LM_ORS and UM-U_ORS pass laterally westwards into, within the hangingwall to the Stack-Skerry Fault Zone (Figs 5.10, 5.11 and 5.12).

The chaotic seismic facies character of Unit A (Fig 5.11 and 5.12) could simply represent seismic noise or alternatively it may represent a lateral depositional facies change from the well stratified seismic events within Sequences L-LM_ORS and UM-U_ORS. Both of these interpretations are plausible, although the latter is the preferred interpretation of this study. This is because, firstly Unit A can be mapped on different vintages of seismic within the basin and therefore with different acquisition parameters (e.g. Figs 5.11 and 5.12), and secondly, seismic imaging of lacustrine rift basins in similar settings, such as south-eastern China (e.g. Changsong et al. 1991) and East Africa (Tiercelin 1991; Karp et al. 2012), commonly display chaotic seismic reflections in close proximity to faults, which are frequently interpreted as proximal footwall sourced fan deposits (e.g: Figs 5.13 and 5.14). Additionally, Rogers and Astin (1991) reported the occurrence of proximal footwall-sourced alluvial fan deposits in the Inner-Moray Firth region of the Orcadian Basin.

Thus, this study considers that it is reasonable to interpret Unit A as representing proximal alluvial fans deposits that were sourced from the footwall region of the Stack-Skerry Fault Zone. The seismic facies boundary between Sequence L-LM_ORS and Unit A can be mapped across the Stack-Skerry sub-basin, to give a corresponding depositional facies map for Sequence L-LM_ORS, as shown in in figure 5.10. The

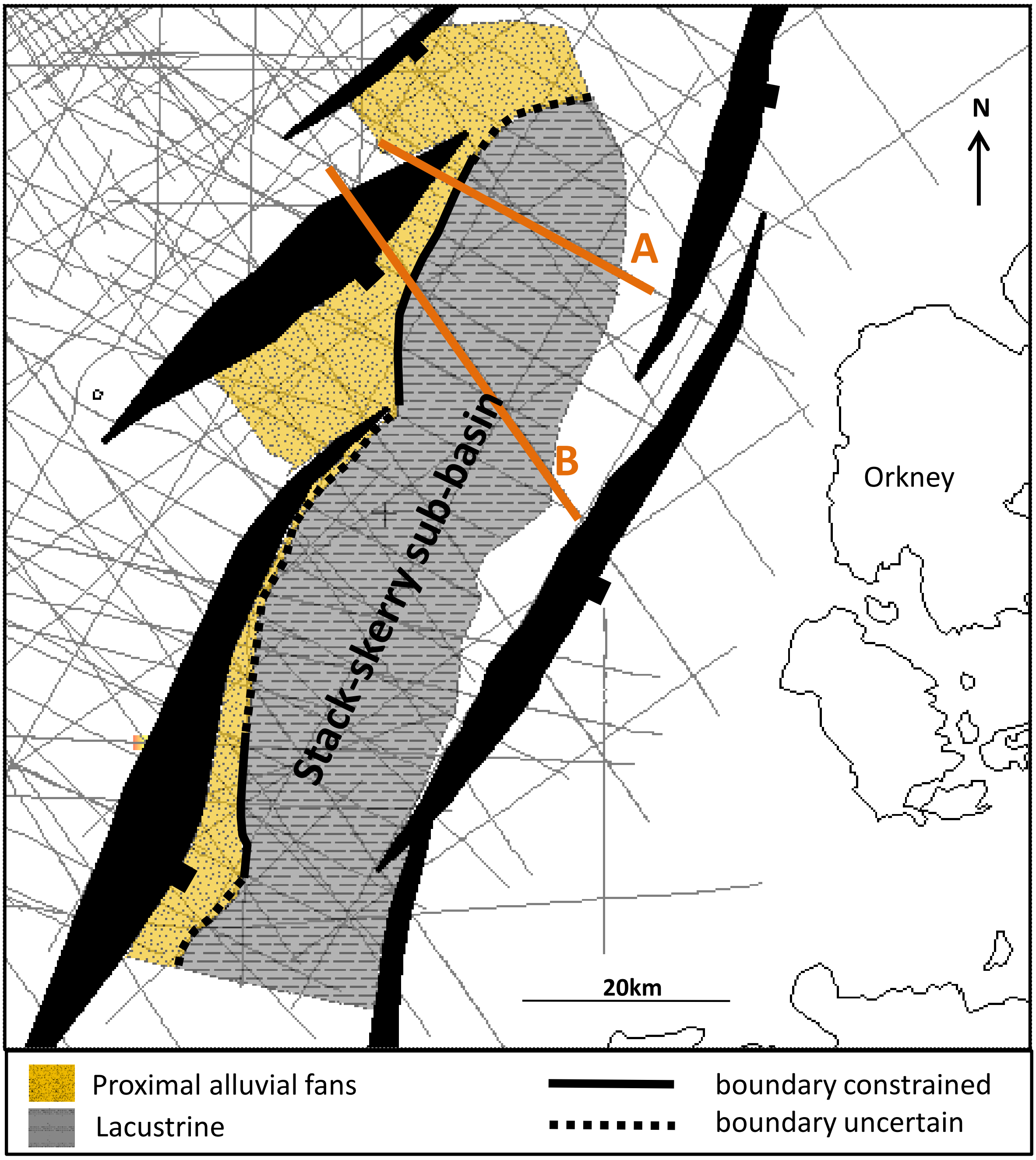


Figure 5-10. Seismic facies interpretive map of Sequence L-LM_ORS within the Stack-skerry sub-basin. Sequence L-LM_ORS comprises well stratified continuous seismic reflections, that are interpreted to represent lacustrine sediments. These continuous reflections pass laterally westwards into a distinct seismic facies unit (Unit A), comprising chaotic and structureless amplitudes, that is interpreted as proximal footwall sourced alluvial fan deposits. The seismic facies is shown on two type sections: A and B, in figures 5.11 and 5.12 respectively.

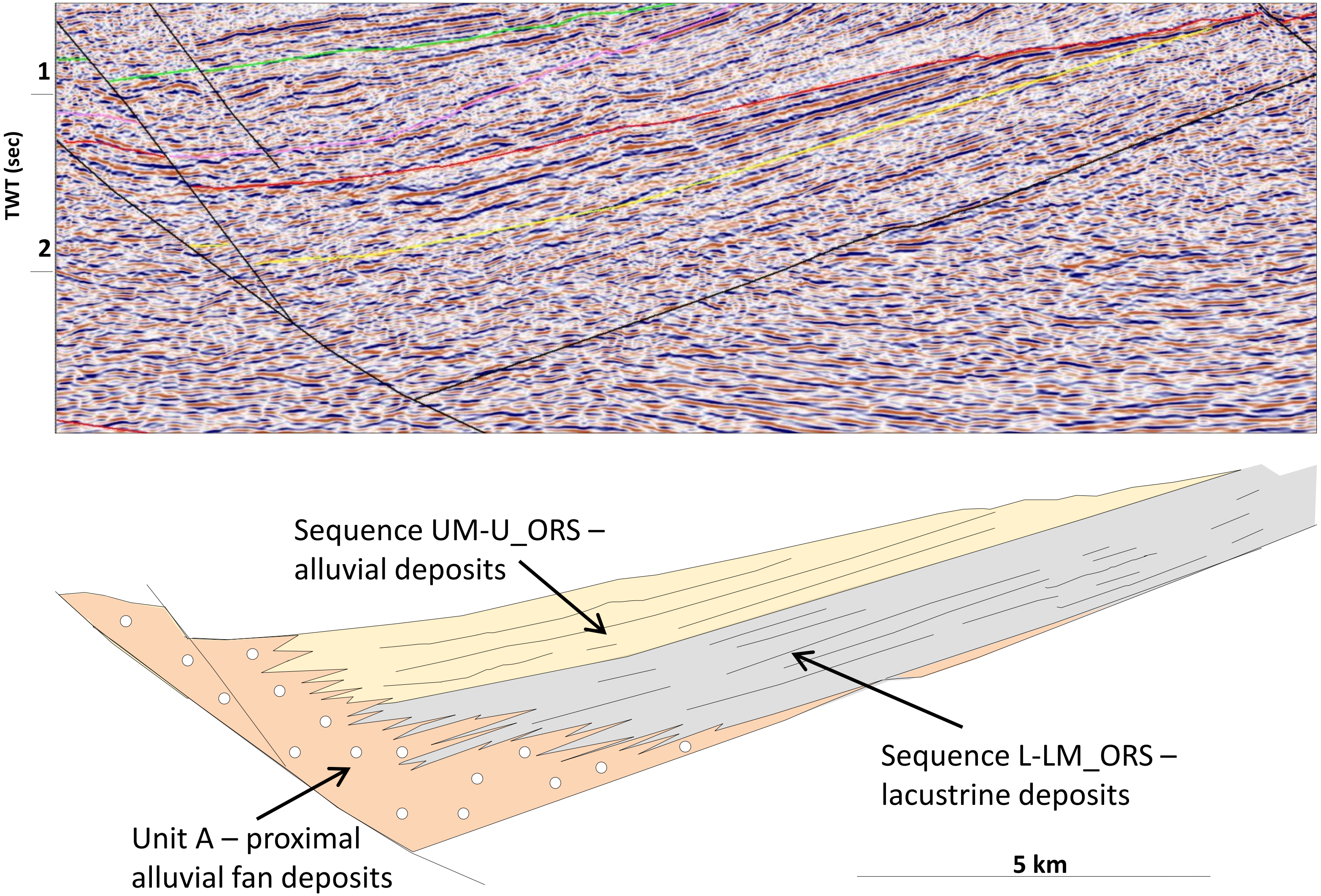


Figure 5-11. Line A, seismic facies interpretation of Sequences L-LM_ORS and UM-U_ORS. Sequences L-LM_ORS and UM-U_ORS can be sub-divided by the recognition of a distinct seismic facies unit (Unit A), comprising chaotic and structureless amplitudes, that both Sequences L-LM_ORS and UM-U_ORS pass laterally westwards into, within the hanging-wall to the Stack-skerry Fault Zone. For location of Line A see Fig 5.10, and Fig 4.3 – Line 1.

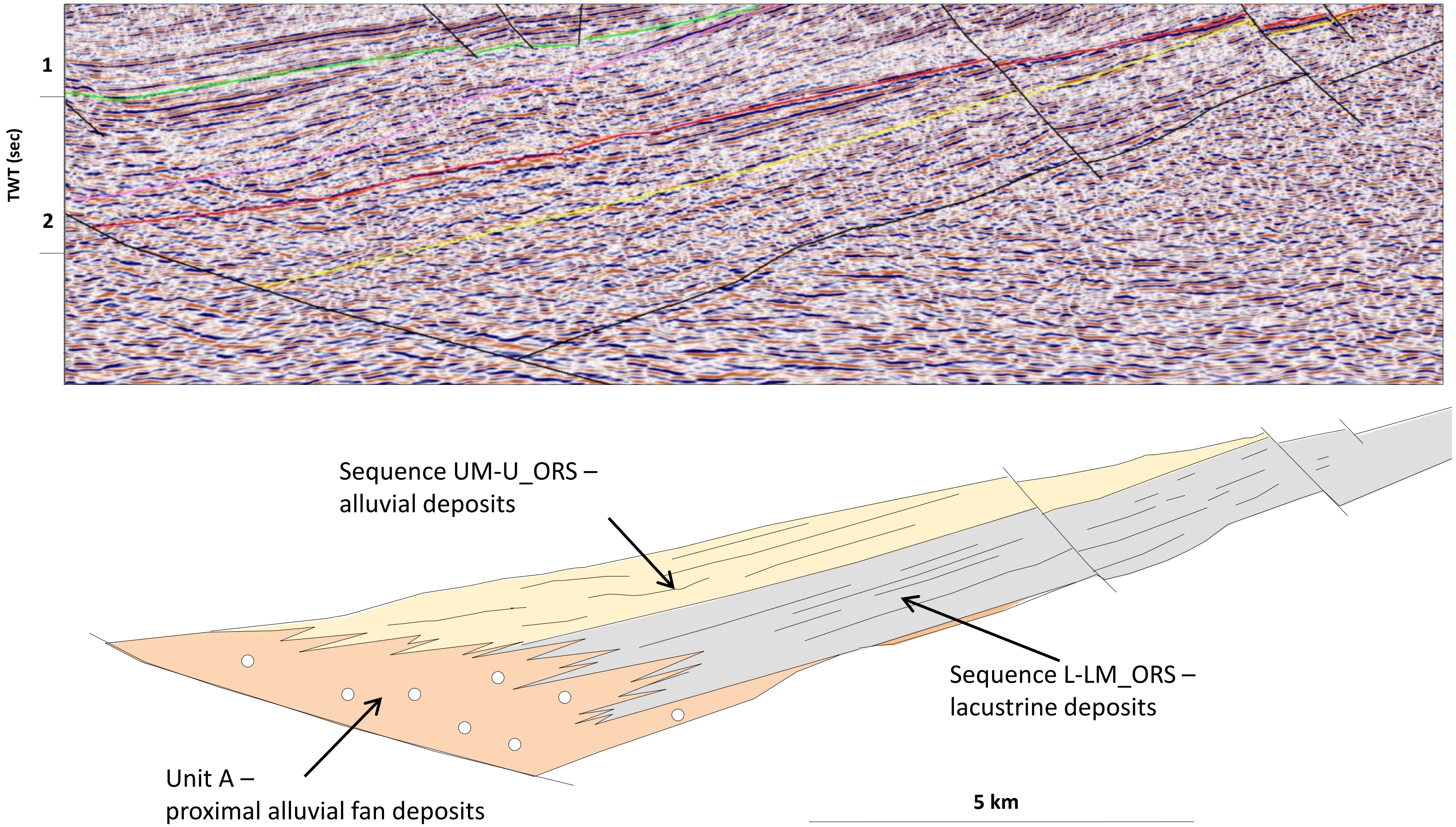


Figure 5-12. Line B, seismic facies interpretation of Sequences L-LM_ORS and UM-U_ORS. Sequences L-LM_ORS and UM-U_ORS can be sub-divided by the recognition of a distinct seismic facies unit (Unit A), comprising chaotic and structureless amplitudes, that both Sequences L-LM_ORS and UM-U_ORS pass laterally westwards into, within the hanging-wall to the Stack-skerry Fault Zone. For location of Line B see Fig 5.10, and Fig 4.3 – Line 2.

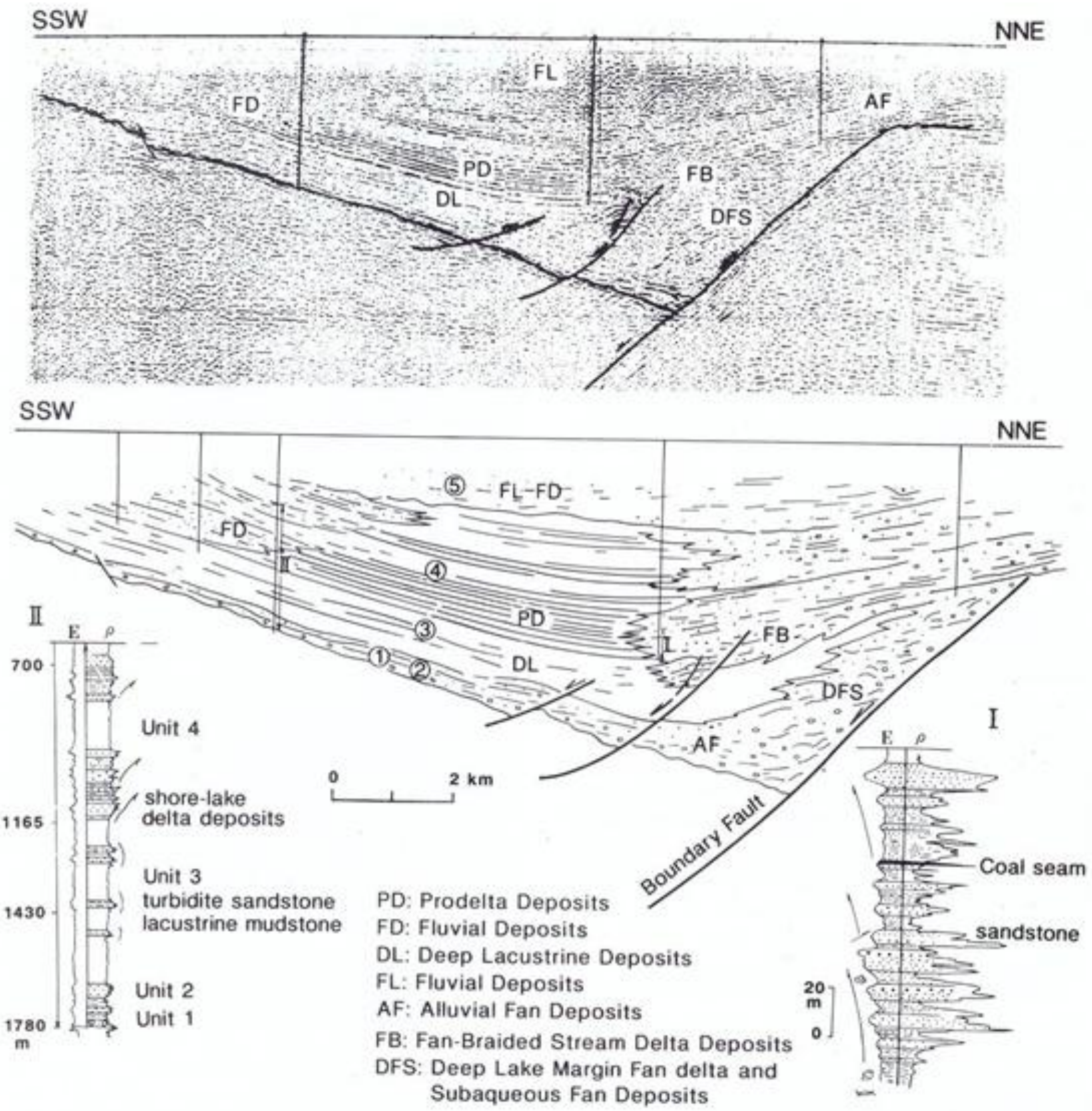


Figure 5-13. Seismic profile and its facies explanation from the Tertiary lacustrine Baise Basin, southeast China (Changsong et al. 1991). The seismic character and distribution of depositional facies within the Baise Basin provides an excellent analogue to the WOB.

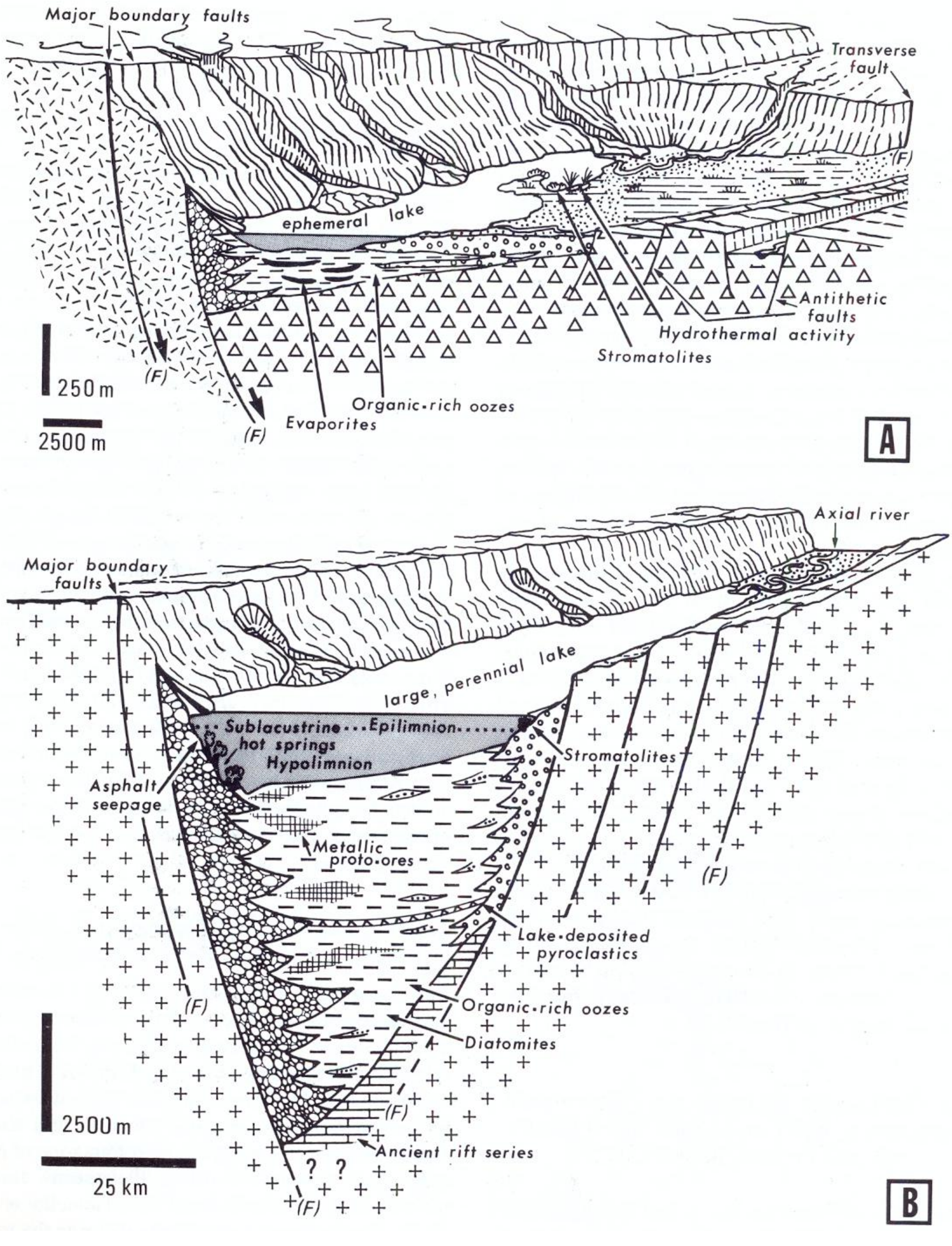


Figure 5-14. Model from Tiercelin (1991) showing distribution of potential facies along lakes in hypothetical segments of the East African continental rift system. Organic rich deposits form in the central regions and alluvial fan deposits form at basin margins. (A) Young, shallow half-graben occupied by a epithermal lake. (B) Ancient, deep half-graben occupied by a large, permanent lake, often stratified.

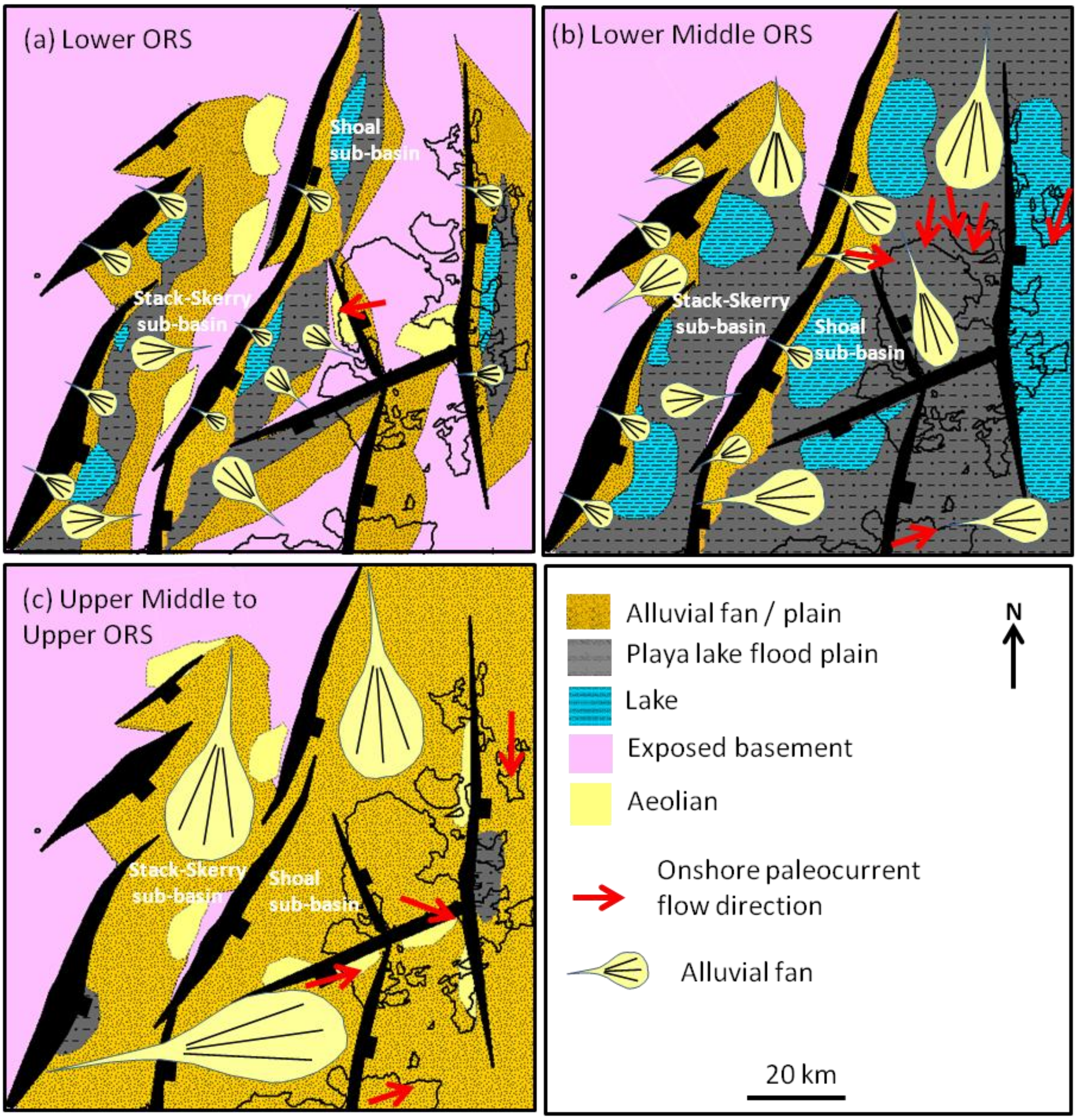


Figure 5-15. Gross depositional environmental (GDE) maps for the Lower, Middle and Upper Devonian. The maps are constrained from offshore seismic interpretation and onshore paleocurrent data obtained during this study and from published studies (e.g. Astin 1990 & Trewin 2002).

boundary between proximal alluvial fan deposits and lacustrine deposits is shown dashed in locations where it is poorly defined and as a continuous line where it can be constrained from the seismic data.

5.2.2.3 GDE map construction – source-rock distribution

Gross depositional environmental (GDE) maps for Lower, Lower Middle and Upper Middle to Upper Devonian have been constructed (Fig 5.15) in order to gain understanding on the potential distribution of source and reservoir rock within WOB. The seismic facies interpretive map for Sequence L-LM_ORS in figure 5.10 has been used in conjunction with Sequence L-LM_ORS and UM-U_ORS isopach maps (Fig 4.12 an 4.13) to constrain possible distributions of lacustrine and alluvial fan deposits within the basin.

The GDE models for the entire interpreted Devonian succession in the basin illustrate that the best source-rock potential is within the Lower Middle Devonian, where it conveys an ephemeral environment, as this represents the dominant environment in the Orcadian Basin during the Lower Middle Devonian (e.g. Rogers & Astin 1991). During wetter periods, lakes probably transgressed the majority of the rift system in the WOB, as suggested by the lateral extent of lacustrine seismic facies within the Stack-Skerry sub-basin (Fig 5.10, 5.11 and 5.12). But whether lakes in the Shoal and Stack-Skerry sub-basin interconnected or not, to form one single large lake, can only be speculated upon, because the sequence is no longer preserved across the Shoal High due to subsequent uplift and erosion (e.g. Fig 5.7). Nonetheless, as the Shoal High appears to have acted as a partial barrier to deposition (e.g. Fig 5.6), then it is plausible that when the lakes were at their deepest, they partially connected across the

Shoal High, creating one single large lake. This view is supported by the observation from other areas of the Orcadian Basin, where deep lake intervals within the Lower Middle Devonian are sometimes deposited across the most proximal environments within the basin, such as basement (e.g. Marshall et al. 2007). Lake water depth estimates are extremely difficult to constrain using wave-base estimates in the absence of reliable estimates of fetch and wind speeds and topography (Astin 1990), but are thought to have rarely exceeded 20 m in depth (e.g. Rogers & Astin 1991).

In section 5.2.2.1, the Lower Middle Devonian depositional drainage pattern in the Shoal sub-basin and Orkney was characterised as being axial through-going drainage towards the south, with relay zones in the Shoal Fault Zone possibly providing access routes for the main channel systems for alluvial fan deposition (Fig 5.6). Therefore, it is conceivable that relay zones in the Stack-Skerry Fault Zone also acted as loci for major channel systems for deposition into the Stack-Skerry sub-basin, with axial-flowing alluvial fans propagating from the north, as shown in the GDE model in figure 5.15. Pronounced footwall topography along the Shoal High, such as the topographic basement highs (e.g. 5.6 and 5.7), could have created reversed alluvial fan drainage towards (e.g. Gawthorpe & Leeder 2000: Fig 5.9) to the west and into the Stack-Skerry sub-basin (Fig 5.15).

Source rock TOC and quality is likely to vary dramatically throughout Sequence L-LM_ORS in the WOB. Large vertical variations in TOC attributed to lake level changes are observed in the onshore sequence (Speed 1999). Speed (1999) analysed kerogen variation across different structural controls on Devonian deposition in Orkney and concluded that the main agents that were detrimental to the formation of source rocks were turbidity currents carrying oxygenated water and sediment that originated from alluvial fan input into lakes. Therefore, TOC content and source-rock quality can be postulated to best be preserved in central areas of the Stack-Skerry sub-basin and away from the main channel systems for alluvial fan deposition, such as relay zones (Fig 5.15).

It is beyond the scope of this research project to comment any further on source-rock distribution in the offshore portion of the WOB, due to the lack of data constraints and therefore the large uncertainties involved. The work presented here could potentially be used as a framework for industry to quantify the probability of source rock presence in the WOB.

5.3 WOB Petroleum System

Figure 5.16 shows a hypothetical WOB petroleum system diagram, as defined in this study. The diagram summarises and illustrates the different elements of the petroleum system relative to their position in the stratigraphic column: reservoir, seal, source, traps, and the main tectonic events distinguished in the previous chapter, which are related to timing of charge and discussed in detail in the next chapter.

A conceptual play cartoon generated to show the potential plays at each stratigraphic reservoir interval in the WOB is shown in figure 5.17. The model illustrates a section running NW-SE across the WOB and is loosely based on a 2D seismic line and onshore analogues. Each play is described systematically in this section. The timing of trap formation relative to that of petroleum generation and migration is critical; if a trap is considered viable, then it must have formed prior to or at the same time as petroleum migration (Gluyas & Swarbrick 2004). As discussed in detail in the next chapter, traps within the basin are considered to have formed before and during hydrocarbon generation, and thus, the present day structural architecture of the WOB

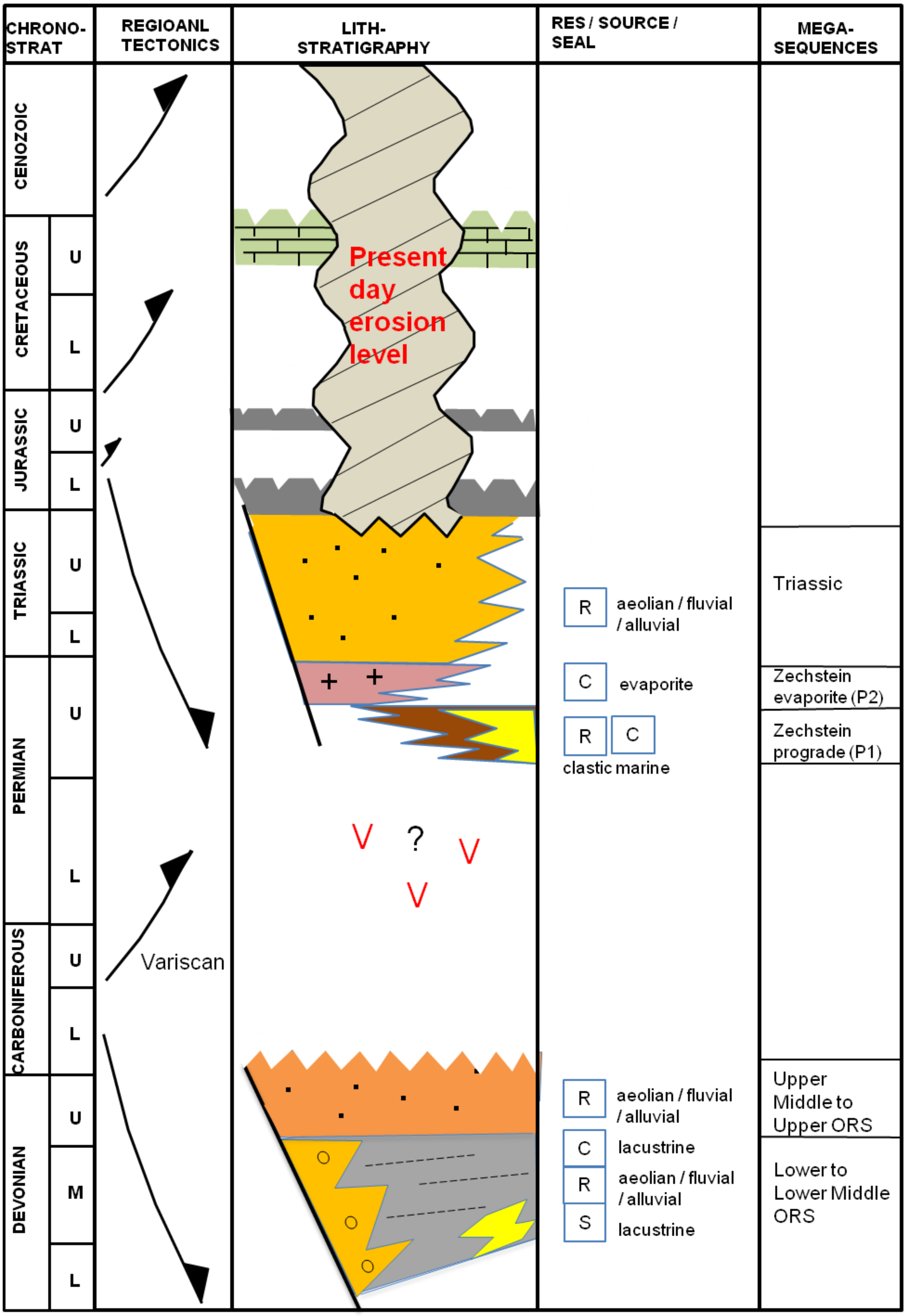


Figure 5-16. Petroleum system diagram for the WOB, as defined in this study

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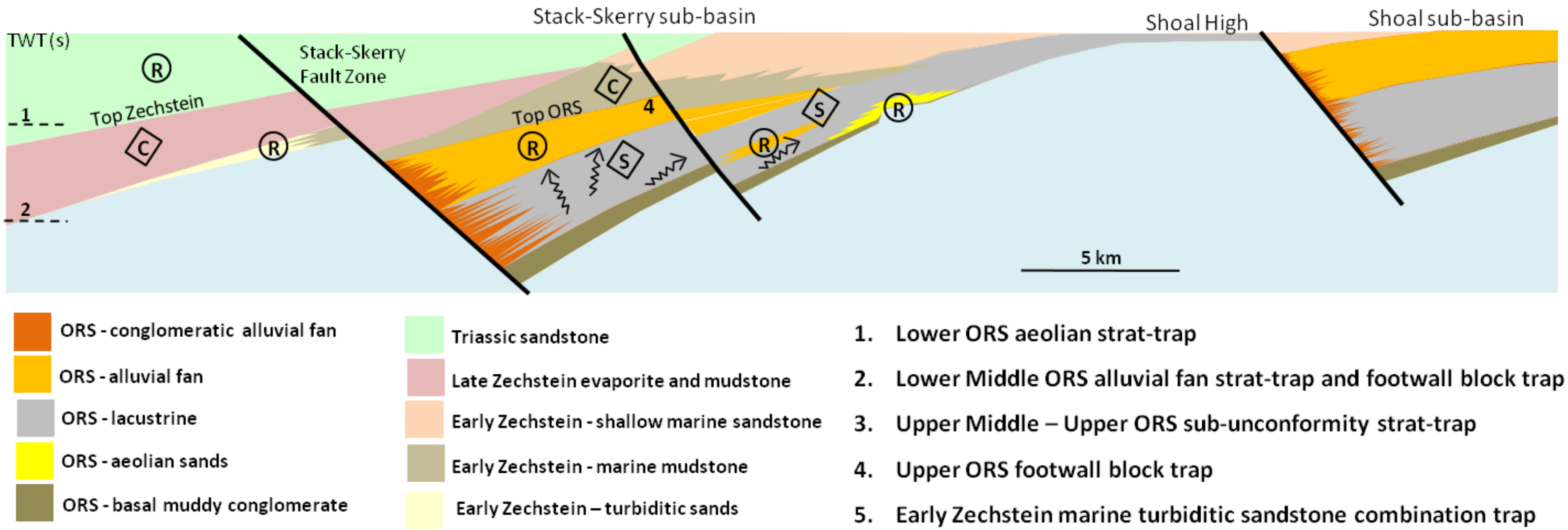


Figure 5-17. Conceptual play model for the West Orkney Basin.

(defined in the previous two chapters) is utilised in this section to assess the presence of traps at each defined play level within the basin.

5.3.1 Petroleum plays

5.3.1.1 Lower Devonian aeolian stratigraphic trap

Lower Devonian rocks outcrop on the western fringes of Caithness and the west mainland of Orkney and are in general considered as having non-reservoir properties, because they consist predominantly of fluvial conglomerates, breccias, mudstones and sandstones, which were deposited in localized drainage patterns sourced from basement highs. As a result, Lower Devonian rocks vary significantly in thickness across the onshore areas of the basin - from zero to a few hundred metres within fault hangingwalls (Trewin 2002).

However, a single localized Lower Devonian aeolian deposit outcrops at Yesnaby (Yesnaby Sandstone Formation: Fig 5.1) on the west of Orkney. The Yesnaby Sandstone Formation consists of up to 200 m of aeolian sandstone. Large scale dune bedding can be seen at outcrop and on sea stacks along the coast at Yesnaby (Fig 5.18). Owen (1994) has reported the sandstone to have porosity of 13% to 25% and permeability of 3mD to 2000mD. The porosity is partially filled with bitumen residues, which may suggest that hydrocarbons where once trapped in the sandstone, before subsequent exposure and loss of volatiles (Astin 1990).

The localised distribution of the Yesnaby Sandstone Formation has been reported to have been the result of wind-blown sands being trapped against a gneiss basement hill (Trewin 2002). This view was tested during this studies field trip to Orkney, by structural mapping of the Yesnaby outcrop, with generation of a field-map and cross-section, as shown in figure 5.19. The map and cross section clearly illustrate that the Yesnaby Sandstone Formation stratigraphically pinches-out towards the south over the paleo-basement hill and therefore supporting previous interpretations of a localised distribution (Trewin 2002). The Yesnaby Sandstone Formation or any equivalent aeolian sandstone, are not found at any other onshore basement outcrops.

Aeolian reworking of alluvial sands with deposition against topographic highs is a prominent characteristic in many arid and semi-arid basins (Einsele 2000). For example, an excellent modern day analogue to the depositional environment of the Yesnaby Sandstone Formation is the ‘Great Sand Dune’ of the San Luis Valley of Colorado (Fig 5.20 and 5.21). The Great Sand Dune is trapped at a specific location where the Sangre de Cristo Mountains buckle inward, due to the result of the San Lus Valley’s unique wind patterns (McCalpin 1983).

If the Yesnaby Sandstone Formation outcrop does indeed represent an exhumed oil field (e.g. Marshall & Hewett 2003), then the trapping mechanism would appear to be due to the discontinuous distribution of the Yesnaby Sandstone Formation forming a stratigraphic pinch-out trap, with the Lower Middle Devonian lacustrine sequence providing a top seal and basement providing a bottom a seal. Therefore, the trap can be classified as a buried depositional relief trap (e.g. Magoon & Dow 1994); where the Yesnaby Sandstone Formation was transgressed by the Lower Middle Devonian lacustrine sequence. Other than the possibility that hydrocarbons may have once been trapped at Yesnaby (e.g. Marshall & Hewett 2003), the sealing capacity of the Lower Middle Devonian lacustrine sequence is largely unknown, and is notoriously difficult to predict (e.g. Cartwright et al. 2007). Any lithology can act as a seal to a petroleum accumulation.

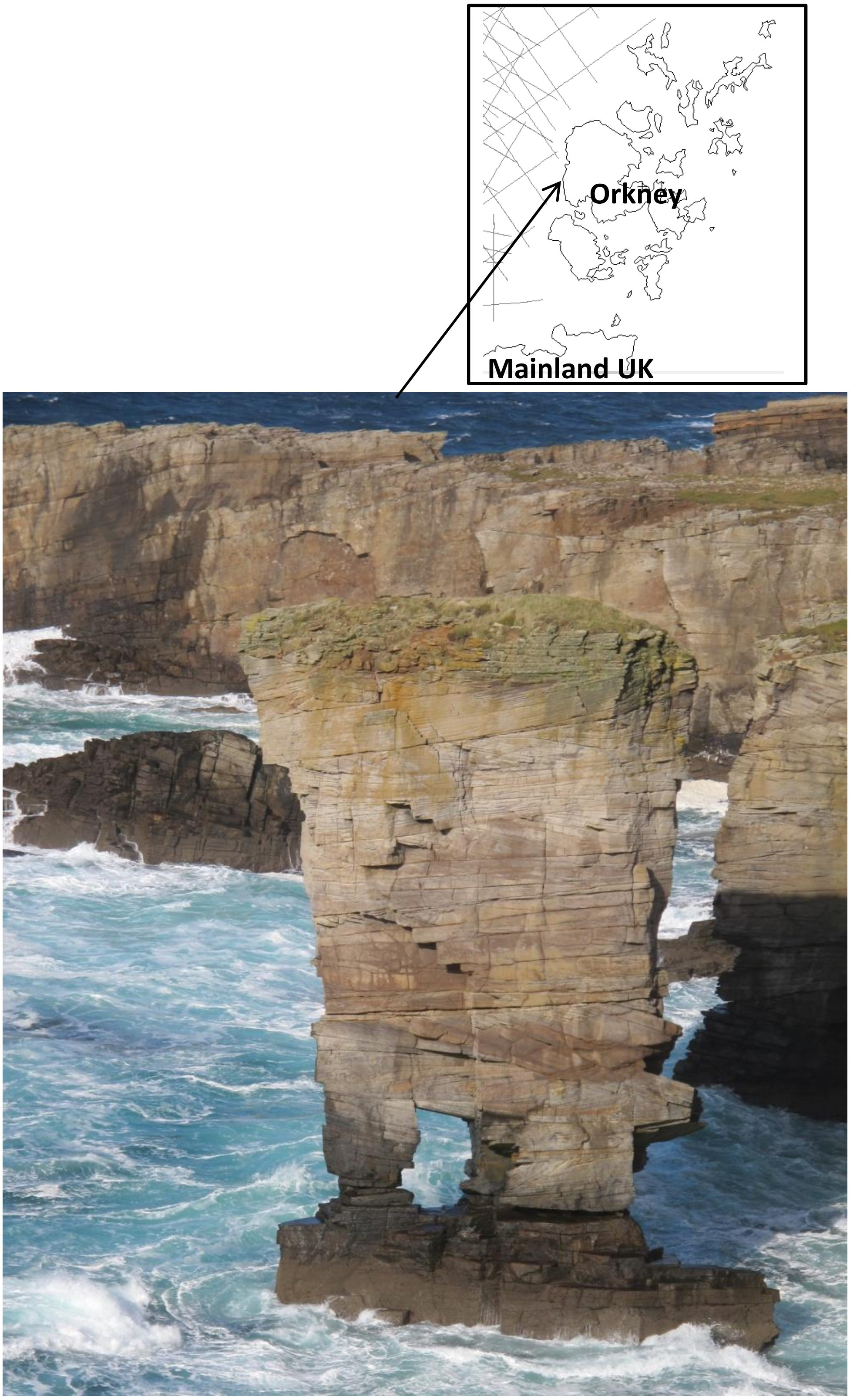


Figure 5-18. GR:X322109, Y1015211 – looking west. Sea-stack displaying large scale dune bedding of the Yesnaby Sandstone FM (western coast of Orkney). The porous desert sand is occasionally blackened with bitumen, suggesting that at some time in the past, it may have been a reservoir for hydrocarbons.

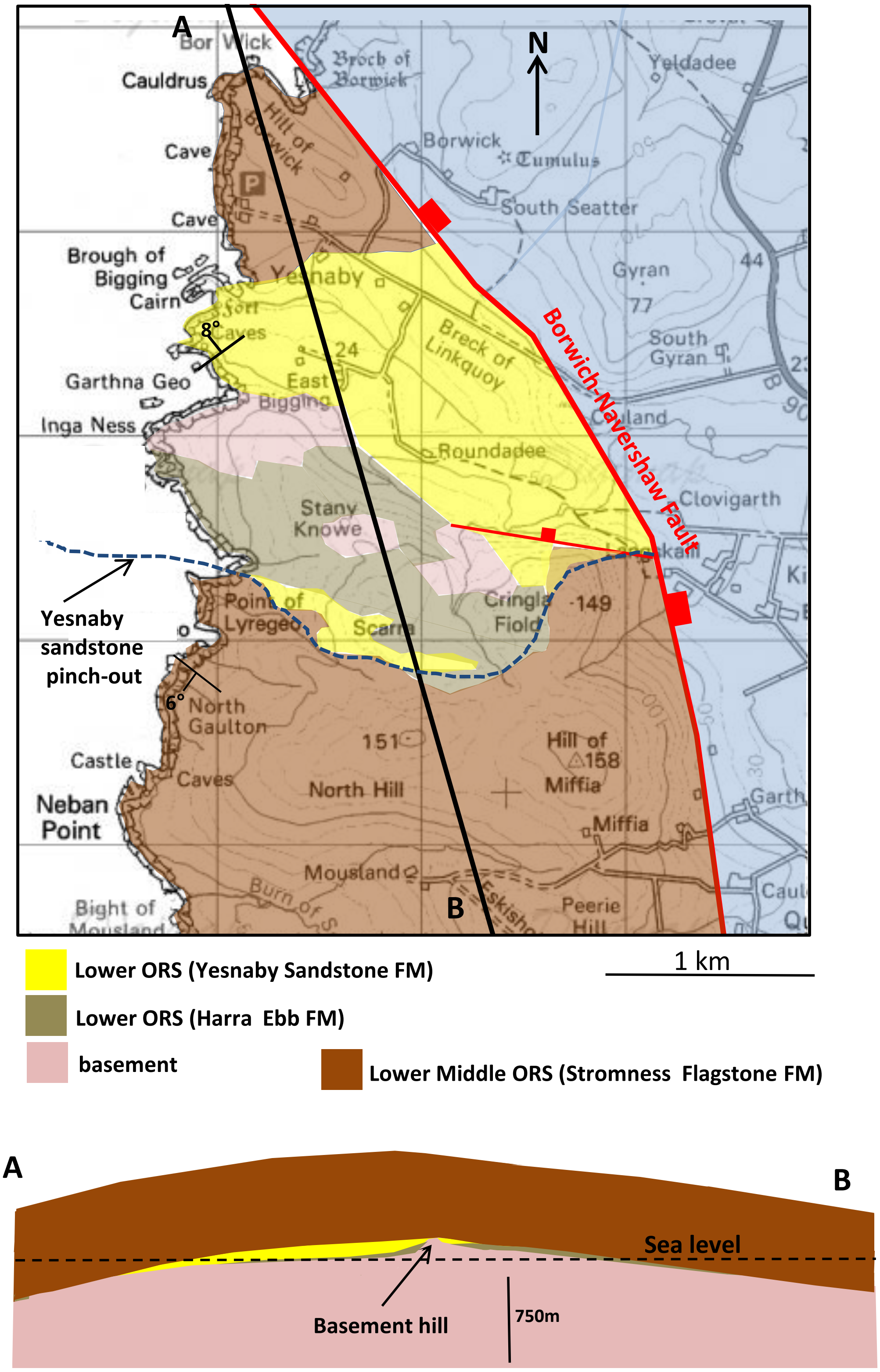


Figure 5-19. Geological map from field mapping the Yesnaby area and corresponding speculative north-south cross-section. The Yesnaby Sandstone FM is interpreted to have been trapped against a basement gneiss paleo-hill. The apparent discontinuous and localised distribution of the Yesnaby Sandstone Formation, suggests that it is an exceptionally high risk play-concept to locate in the offshore potion of a WOB.

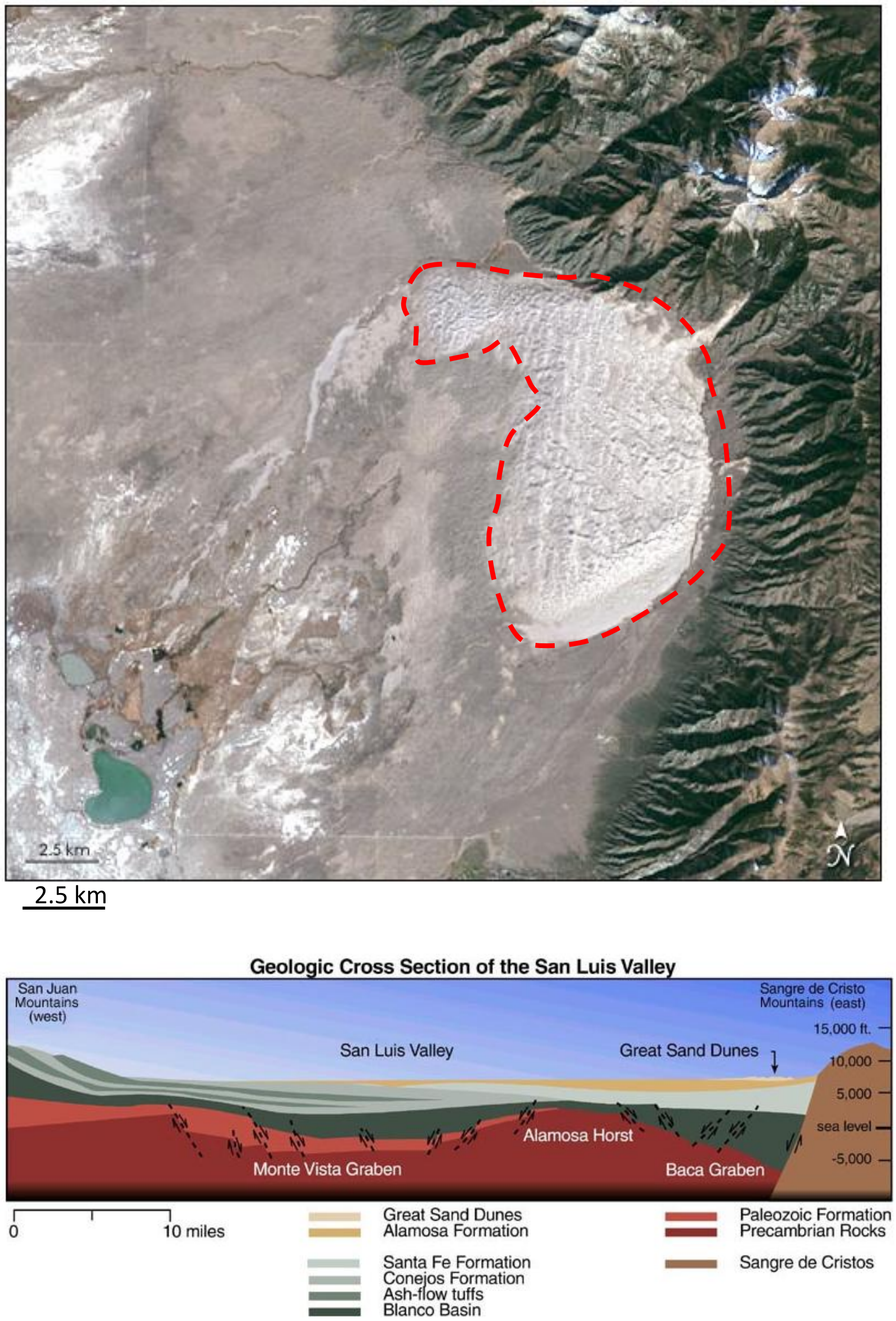


Figure 5-20. Analogue to the Yesnaby Sandstone FM – The Great Sand Dune of the San Luis Valley. The subsiding San Luis Valley has created a catchment for fluvial, aeolian sands, volcanic ash-flow tuffs, clays and lake deposits. The Great Sand Dunes nestled at the foot of the Sange de Cristo Mountains.

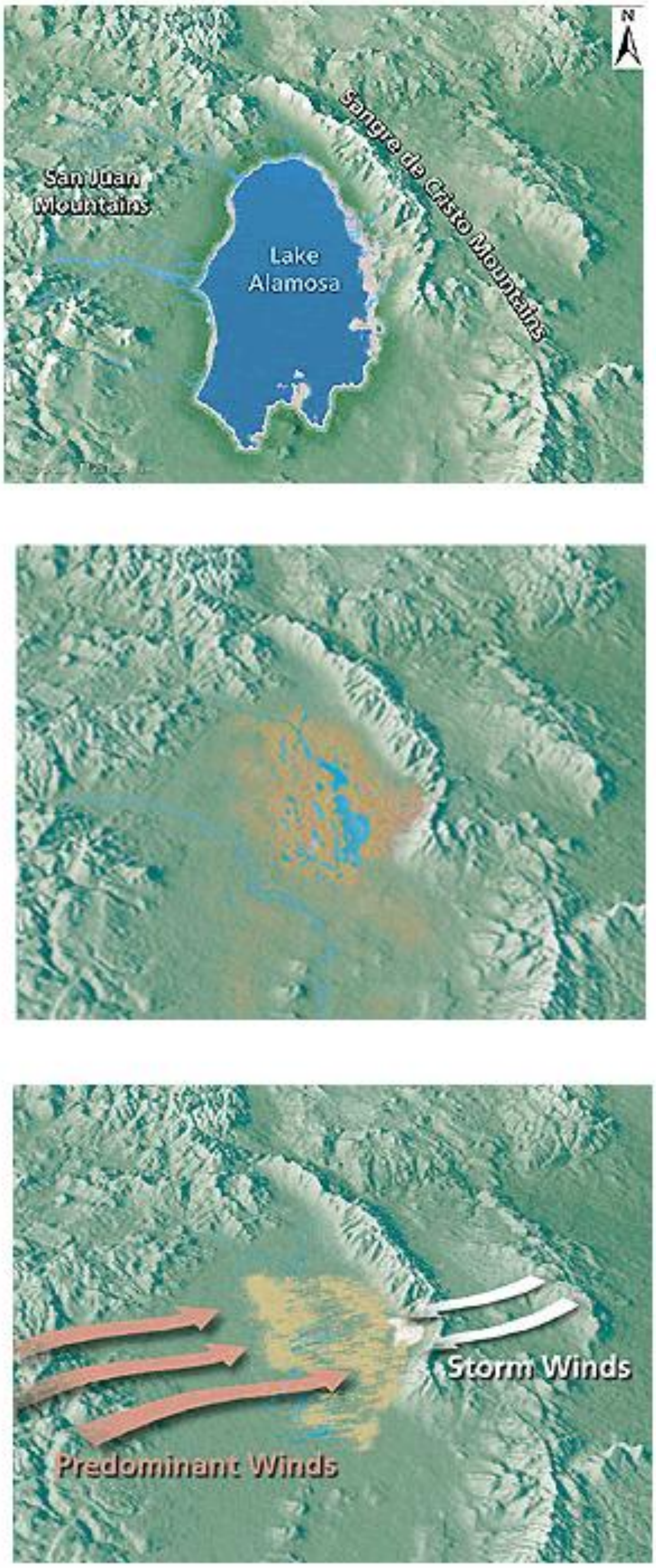


Figure 5-21. Depositional model for the Great Sand (from the National Park Service 2014) - excellent analogue to the Yesnaby Sandstone FM. Desert winds trapped the sands at the base of the mountains. Climate change has controlled the extent of the lake, where in wet periods the lake would flood across the flat valley floor for 10’s of km, stopping at the foot of the mountains. In dry periods it would retreat forming sabkha wetlands.

However, attributes that favour a rock as a seal include high ductility, large thickness, wide lateral extent and small pore size. The most common lithology that forms a petroleum seal is mudrock, due to its favourable pore size (Gluyas & Swarbrick 2004).

The Lower Middle Devonian lacustrine succession consists of cycles of deep lake to playa-lake environments, with the latter being the dominant environment. A critical result of this is that the sequence has a very high sand content. For example, numerous sandstone fluvial beds can be observed at outcrop (e.g. Fig 5.2 and 5.4), that could likely compromise seal integrity, by acting as carrier beds to hydrocarbons (e.g. Alan & Alan 2006). Additionally, the sequence is highly fractured at outcrop (e.g. 5.22), adding to risk with seal integrity (e.g. Cartwright et al. 2007). Although, the succession may have been more highly deformed than its equivalent in the offshore portion of the WOB, because Late Carboniferous inversion was more intense onshore (discussed in detail in section 4.2.1) and therefore direct comparisons between onshore and offshore should be treated with caution.

This study has not been able to distinguish seismic evidence for Lower Devonian aeolian sandstones onlapping basement topography in the offshore portion of the WOB. This could be due to the seismic data being of too low resolution. For example, the Yesnaby Sandstone Formation and the basement hill it onlaps, have a maximum vertical height of about 200 m (Fig 5.19), which is the equivalent to about 0.1s TWT. Extensive structural seismic mapping of the top of the basement offshore in Chapter 3, has shown the top basement to be generally planar at the seismic scale, although a few areas of apparent top-basement undulation can be seen on some of the reprocessed seismic sections (e.g. Fig 5.11 and 5.12). Furthermore, the apparent

Figure 5-22. GR: X323432, Y:1008825 - looking east. Outcrop picture of the Lower Middle Devonian lacustrine sequence that outcrops on the west of Orkney. The succession is highly fractured onshore, which could compromise seal integrity. Picture taken during fieldtrip to Orkney.

lateral extent of the Yesnaby Sandstone Formation onshore is less than the seismic dip line spacing (about 5 km) offshore.

Thus, it is not possible to identify potential areas within the basin where Lower Devonian aeolian sandstone reservoir targets may reside, because of the resolution and quality of the 2D seismic dataset. Nonetheless, the apparent discontinuous and localised distribution of the Yesnaby Sandstone Formation, suggests that it is an exceptionally high risk play concept to locate in the offshore portion of a WOB. Aeolian facies may be resolved in the basin if 3D seismic was acquired.

5.3.1.2 Lower Middle Devonian intra-lacustrine alluvial fan play

Reservoir facies within rift-lake settings are most commonly associated with near-shore, deltaic, subaqueous fans and turbidite environments. Subaqueous fan deposits commonly provide the best reservoir potential, and as such, are the main exploration focus in lacustrine basins (Katz 2001). Reservoir potential subaqueous fan deposits have not been identified in the Orcadian Basin, because 90% of the Middle Devonian lacustrine succession comprises desiccated playa-lake associated sediments, where water depths rarely exceeded 20m in depth (e.g. Rogers &Astin 1991).

An alternative reservoir target to sub-aqueous deposits in the Orcadian basin, are thick alluvial fan intervals within the Middle Devonian lacustrine succession. These have been correlated across wells in the Moray Firth region of the Orcadian Basin, as shown in figure 5.23. These intervals are dominated by conglomerates and sandstones, with minor intercalations of finer grained lithologies. The sandstone dominated sections can be up to 250 m thick and have porosities of 20% (Marshall & Hewett 2003). Thus, with analogy to the Moray Firth, reservoir thickness Lower

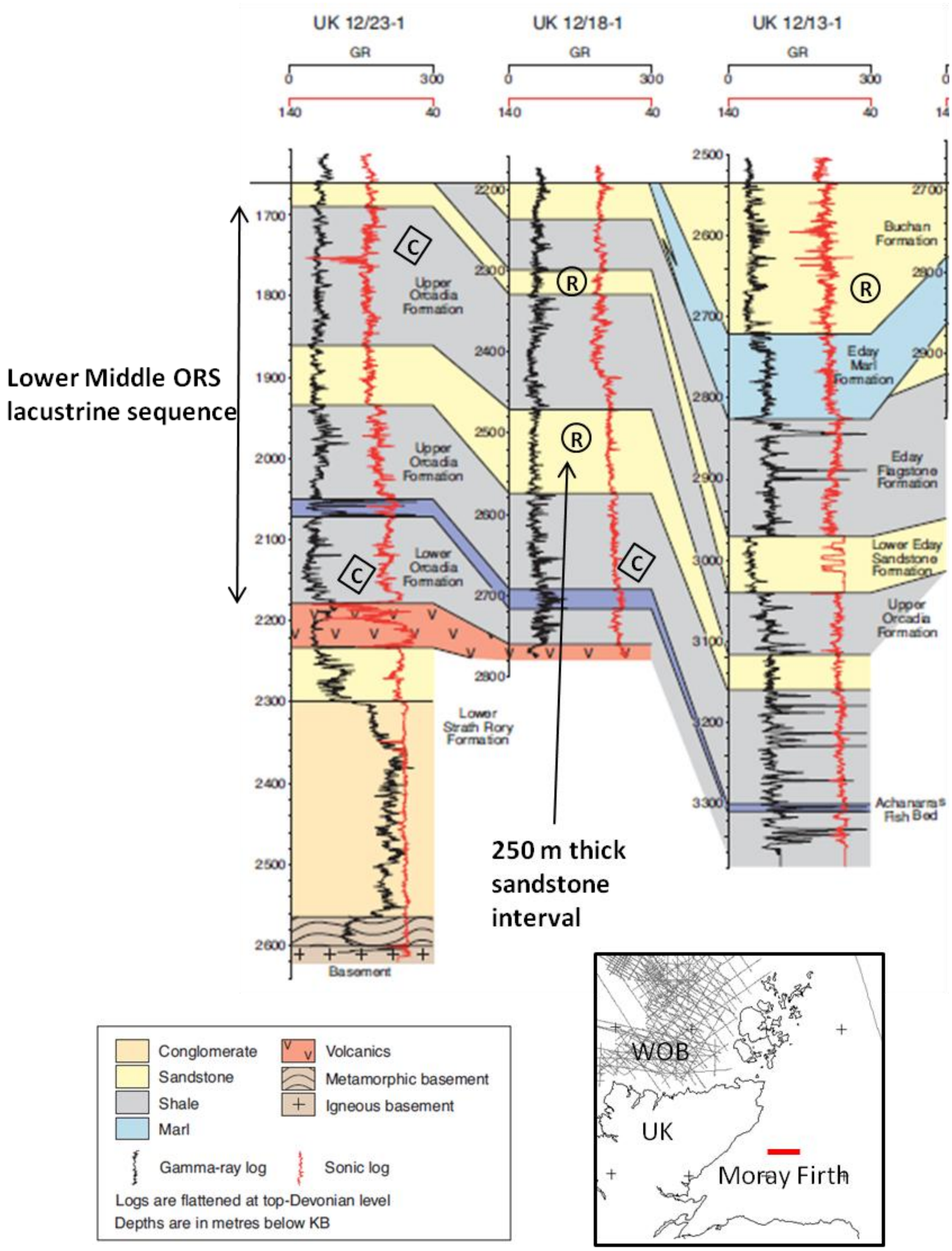


Figure 5-23. Well correlation across the Moray Firth region of the Orcadian Basin, from Marshall & Hewett (2003). Red line on map shows location of wells. Within the Lower Middle ORS sequence, a thick 250 m sandstone interval is apparent. The sandstone consists of alluvial fan deposits, that can have porosities of 20% (Marshall & Hewett 2003). Similar reservoir thick Lower Middle Devonian alluvial fan deposits may also exist within the lacustrine sequence in the WOB, and therefore provide a play concept.

Middle Devonian alluvial fan deposits may also exist within the lacustrine sequence in the WOB and is hereby considered as a potential play concept.

Examples of alluvial fan reservoirs include the Chaunoy field in France (Eschard et al. 1998) and the Quiriquire field of Venezuela (Salvador & Leon 1992). Where alluvial fans do occur as reservoirs, they are regularly not very productive, because they normally show a disorganized aggregation of zones of porous and permeable debris flow and mud-flow deposits. The more distal portions of alluvial fans have greater chance of showing reasonable reservoir quality - where there is less inter-bedding of impermeable mudflow and debris flow deposits (e.g. Shepherd 2009).

Further reducing the quality of alluvial fan reservoir systems is the intermittent tectonism within rift settings and the rapid climatically induced changes in lake level, which results in large internal reservoir heterogeneity, with the potential for the development of numerous intra-reservoir flow barriers and baffles (Bracken 1994). In the Oligocene of the Bohai basin (China) these intervening mudstone baffles can achieve thicknesses in excess of 20 m (Katz & Liu Xingcai 1998), resulting in limited reservoir volume.

As described in detail in section 4.2.1, it is not possible to distinguish intra-lacustrine alluvial fan deposits on seismic within the WOB, because of the quality and resolution of the 2D seismic dataset. Nevertheless, the Lower Middle Devonian GDE model in figure 5.15 can be used speculatively to facilitate prediction of the main alluvial fan channel systems and therefore the most likely locations to create inter-fingering of sandstone (reservoir) and lacustrine (source and seal) facies within the basin, as shown in figure 5.24. Similar approaches to predicting reservoir distribution in frontier lacustrine basins have been used by Richards et al. (2006) in the Falkland

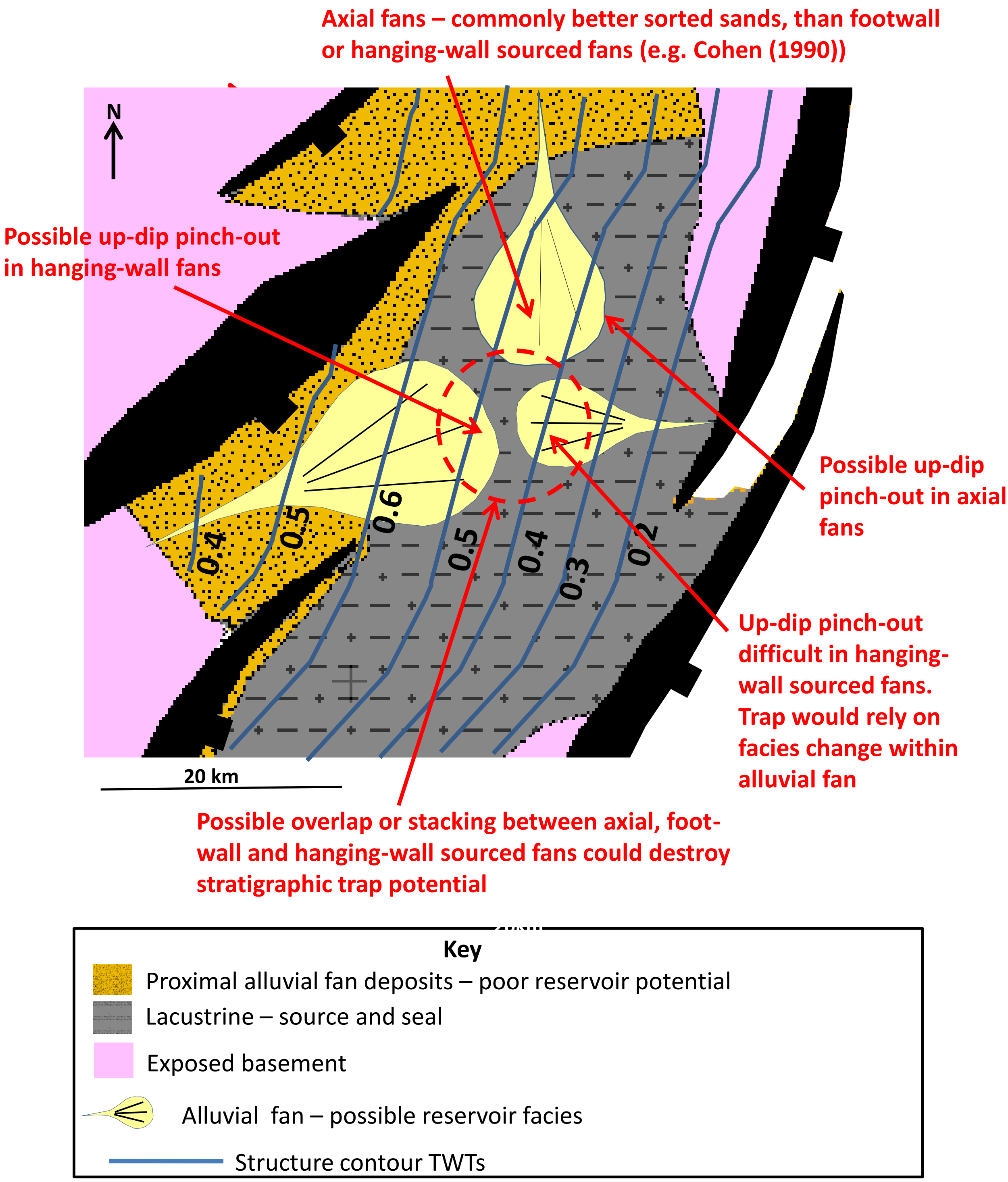


Figure 5-24. Speculative Lower Middle Devonian GDE map to show possible intra-lacustrine alluvial fan stratigraphic trap potential in the Stack-skerry sub-basin. The map is constrained from offshore seismic facies interpretation and onshore paleocurrent data.

Island Basins.

The size of alluvial fans that may propagate into a basin varies significantly and is related to the area of the drainage basin, climate, rock lithology in the drainage basin, tectonic activity and the space available for fan growth (Blair & McPherson 1994). It is plausible that the proximal deposits interpreted on seismic (e.g. Fig 5.11 and 5.12) may represent the proximal regions of alluvial fans that have propagated into the Stack-Skerry sub-basin and as a result are probably of poor reservoir quality (e.g. Magnavita & da Silva 1995; Shepherd 2009), and that reservoir quality may only exist to the east of these deposits, towards the central areas of the half grabens (Fig 5.24).

As described in section 5.2.2.1, relay zones within the Stack-Skerry fault Zone most likely provided the main loci for channel systems for alluvial fan deposition into the Stack-Skerry sub-basin and therefore the largest alluvial fans can be postulated to have accessed the Stack-Skerry sub-basin via such structures, as shown in figure 5.24.

Large axial flow alluvial fan systems, propagating from the north into the Stack-Skerry sub-basin, can also be hypothesized (e.g. section 5.2.2). With analogy to the East African rift system (e.g. Cohen 1990), axial flow fans tend to be more laterally extensive with better sorted sands, when compared to footwall sourced fans and therefore could provide the best intra-lacustrine reservoir potential.

The structure contours in figure 5.24 suggest that footwall-sourced fans could be preferentially able of forming structurally closed, up-dip pinch-out traps. Whereas up-dip stratigraphic closure of axial flow fans is more difficult to envisage. Up-dip pinch-out traps could be difficult in hangingwall-sourced fans, where the stratigraphic trap would rely on facies change within the alluvial fan, which is highly challenging (e.g. Magoon & Dow 1994).

It is evident that the major challenge with an intra-lacustrine alluvial fan stratigraphic-trap play-concept is the presence of an effective trap (discussed in section 5.3.1.1). Any overlap or connectivity between footwall, hangingwall and axial sourced fans, could destroy any chance of a stratigraphic trap (e.g. Fig 5.24). Stratigraphic traps are often regarded as one of the most risky exploration targets and without the support from DHI's, they are rarely drilled (e.g. Atkinson et al. 2006).

Structural or combination structural-stratigraphic traps could also exist within footwall blocks (e.g. Fig 5.25). The latter is difficult to assess due to the reasons described above, whereas the presence of pure structural footwall traps (e.g. Fig 5.25b) can be more easily evaluated, by mapping structural closures (e.g. Gluyas & Swarbrick 2004).

As it is not possible to map individual reservoir intervals (i.e. alluvial fans) within Sequence L-LM_ORS (e.g. section 5.2.2.2), assessment of potential structural closures can only be conducted by structural mapping the top of Sequence L-LM_ORS, as shown in figure 5.26. This method is considered reasonable, because faults that offset the top of Sequence L-LM_ORS also offset the entire sequence, and therefore a structural map of the top of the succession broadly reflects structure at all intervals within the sequence.

Structural closure at top Sequence L-LM_ORS level can only be mapped on one fault in the south of the Stack-Skerry sub-basin (labelled Lead 1), as shown in figure 5.26. Other faults that can be observed to offset the sequence are considerably smaller (maximum throws < 0.05s TWT), and can only be mapped on single seismic lines, making it impossible to evaluate structural closure.

The distribution of lacustrine and proximal facies within Sequence L-LM_ORS (as mapped in section 5.2.2.2) is also illustrated on the structural map of the top of Sequence L-LM_ORS (Fig .26), in order to show the possible distribution of petroleum charge within the basin. The interpreted charge and charge direction is represented with arrows where lacustrine facies is present within Sequence L-LM_ORS and dashed arrows where proximal facies is present, because source-rock presence is considered to be less prevalent in proximal areas (section 5.2.2.2 and 5.2.2.3). The structural closure defining Lead 1 appears to be within the petroleum charge window.

Lead 1 (Fig 5.26 to 5.28) is defined relatively well on 4 dip seismic lines. Sequence L-LM_ORS is fault juxtaposed against the progradational Early Zechstein sequence (refer to section 4.2.2 for age interpretation). If hydrocarbons are to be trapped in hypothetical intra-lacustrine alluvial fan reservoir intervals, within the footwall closure of Lead 1, then the reservoirs must be either fault juxtaposed against sealing lithologies within the Zechstein sequence or that the fault is sealing (e.g. Freeman et al. 1998). The latter is not considered here, due to the major uncertainty in the lithology of the sequences. Therefore, cross fault seal and reservoir presence are the key prospect risks.

Two distinct seismic facies units (Units 1 and 2) were recognised within the Early Zechstein progradational sequence in the previous chapter (4.2.2), and where interpreted to represent shallow marine sandstones (Unit 1), and mudstone and distal marine facies (Unit 2). If this interpretation is correct, then it gives some supporting evidence that Unit 2 facies could provide a seal. However, there is significant uncertainty in mapping the distribution of Units 1 and 2 across the basin, because they

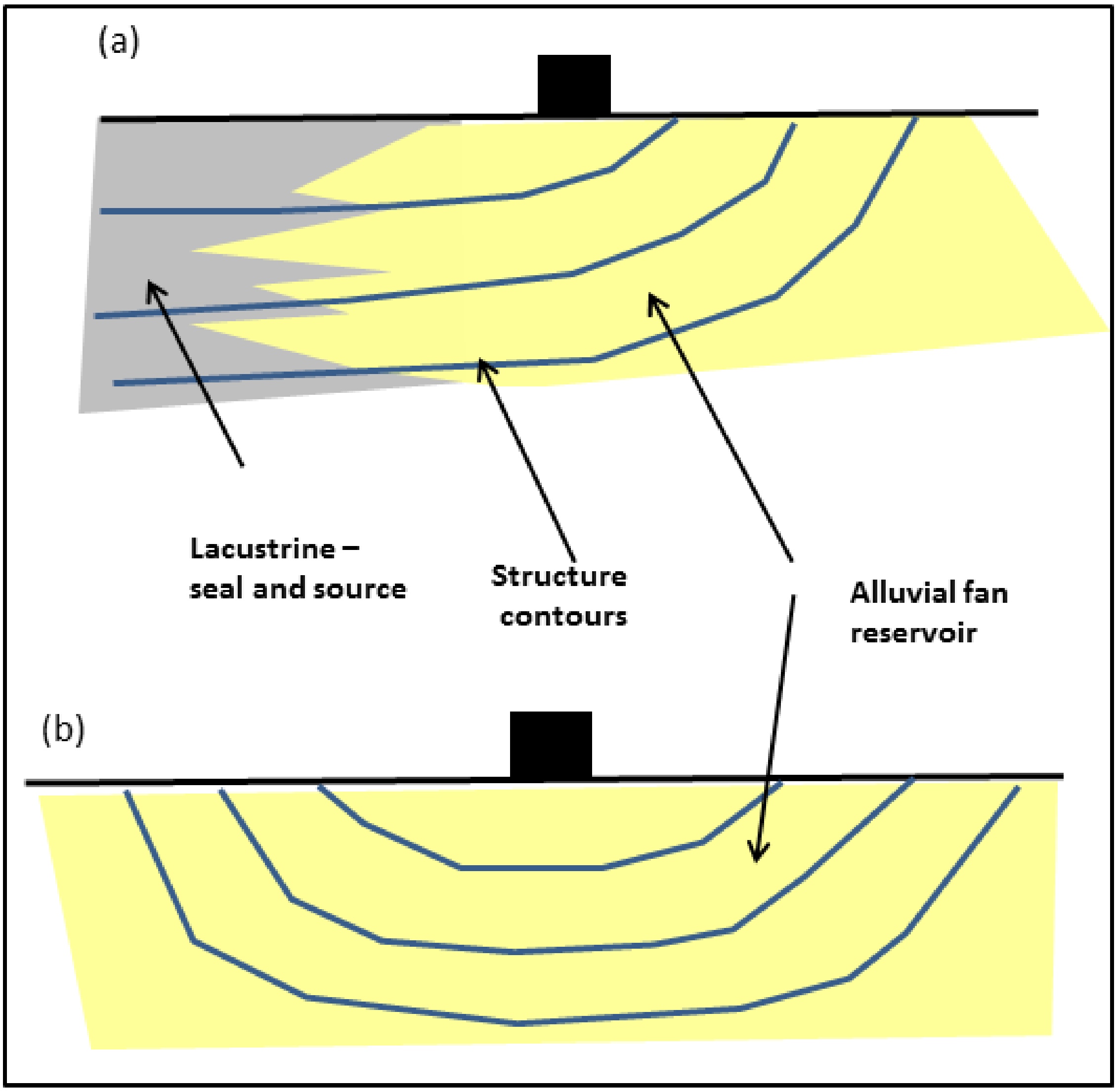


Figure 5-25. Schematic illustration of possible (a) combination structural-stratigraphic trap and (b) pure structural footwall block trap.

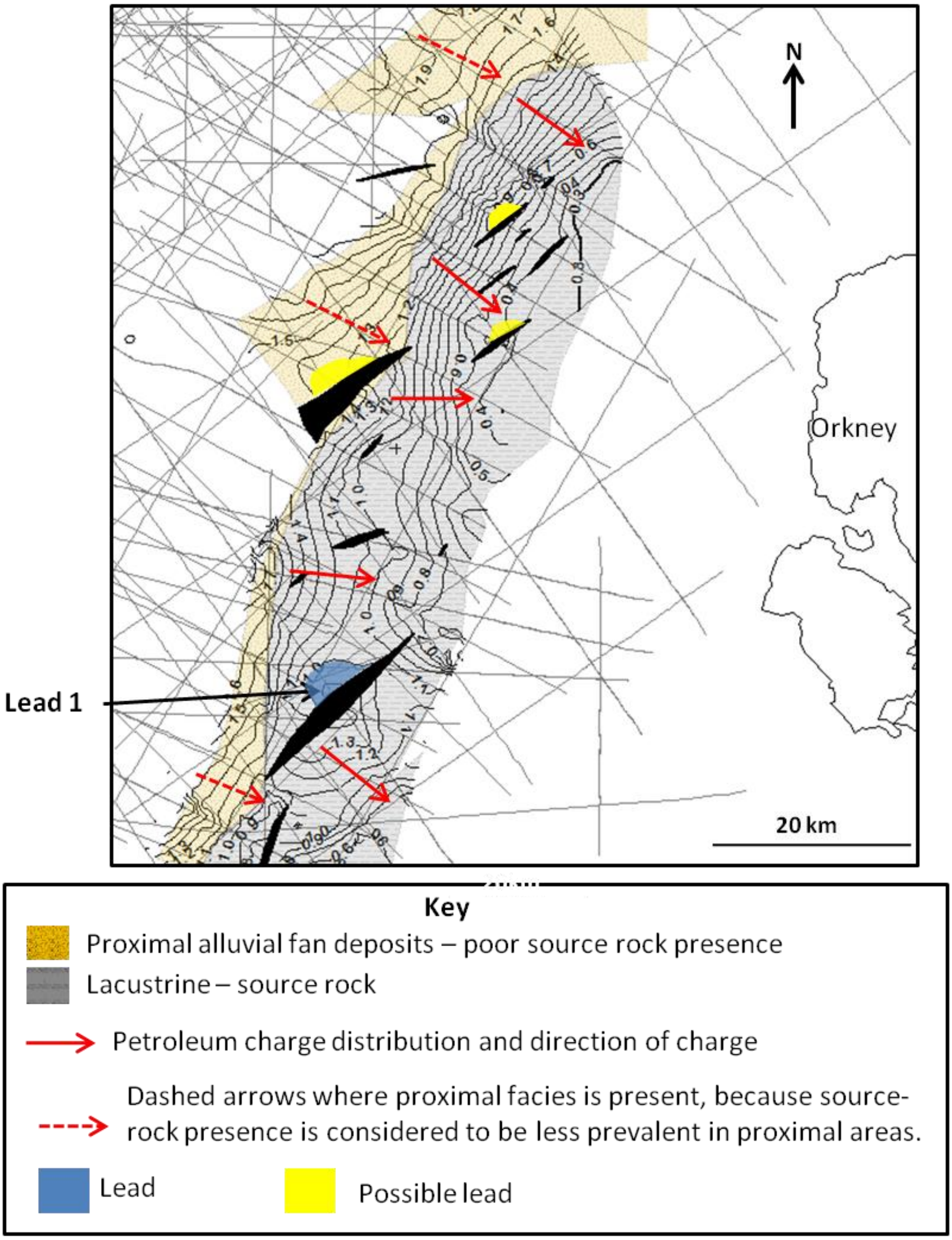


Figure 5-26. Structural map of the top of Sequence L-LM_ORS in the Stack-Skerry sub-basin. Structural closure can only be mapped on one fault in the south of the Stack-Skerry sub-basin (labelled Lead 1). Other faults that can be observed to offset the sequence are considerably small (maximum throws of > 0.05s TWT), and can only be mapped on single seismic lines, making it impossible to evaluate structural closure.

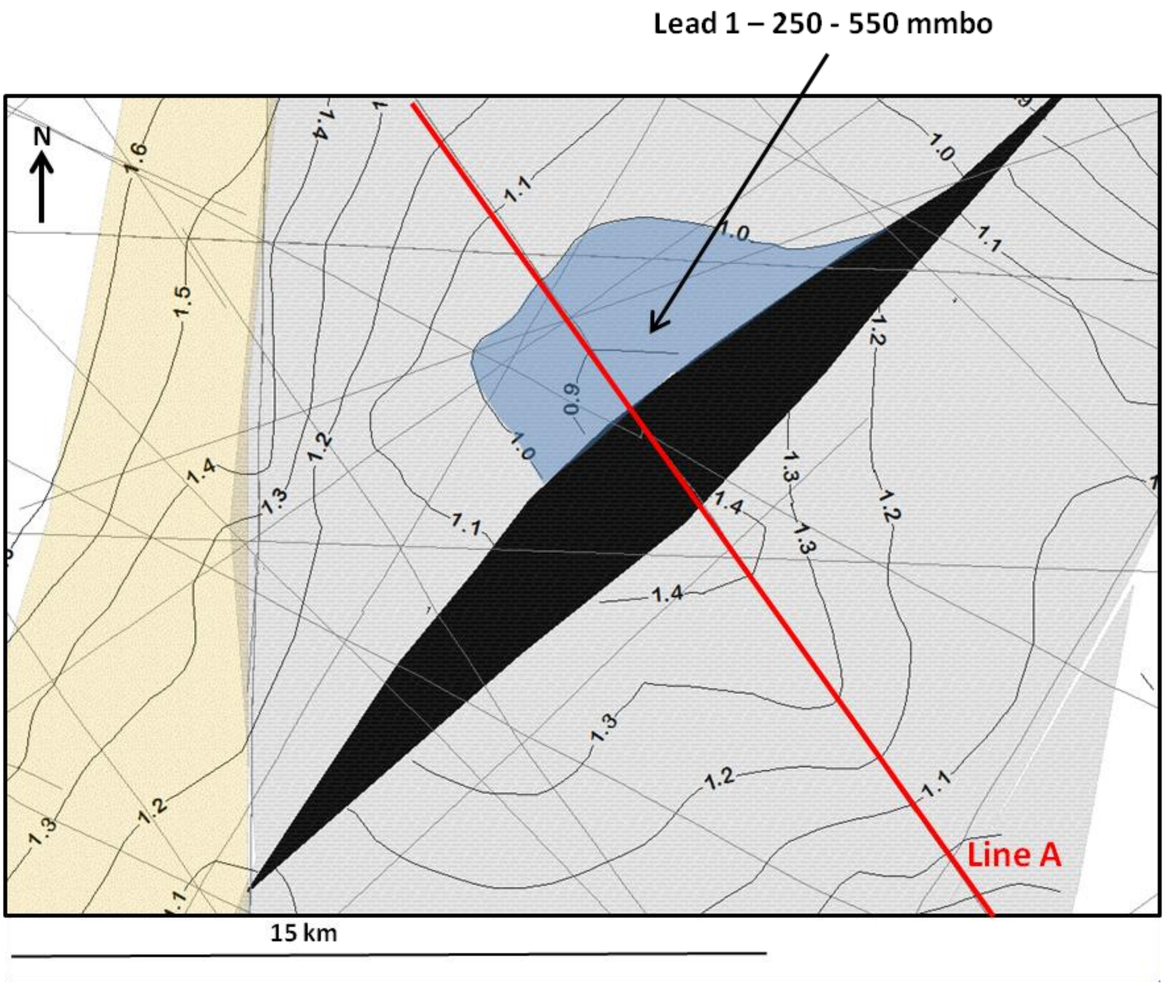


Figure 5-27. Structural map of the top of Sequence L-LM_ORS, showing Lead 1 structural closure. The area = 10, 670 km², and the GRV = 1680525000 m³. The bulk volume (gross-pay-thickness) could hold up to 370 mmbo based on the following reservoir parameters: 12% porosity, 50% net-to-gross, 70% oil saturation and a formation volume factor of 1.2. Note – 370 mmbo is likely an underestimate due to the contour interval. The area may be nearer to 20 km^2.

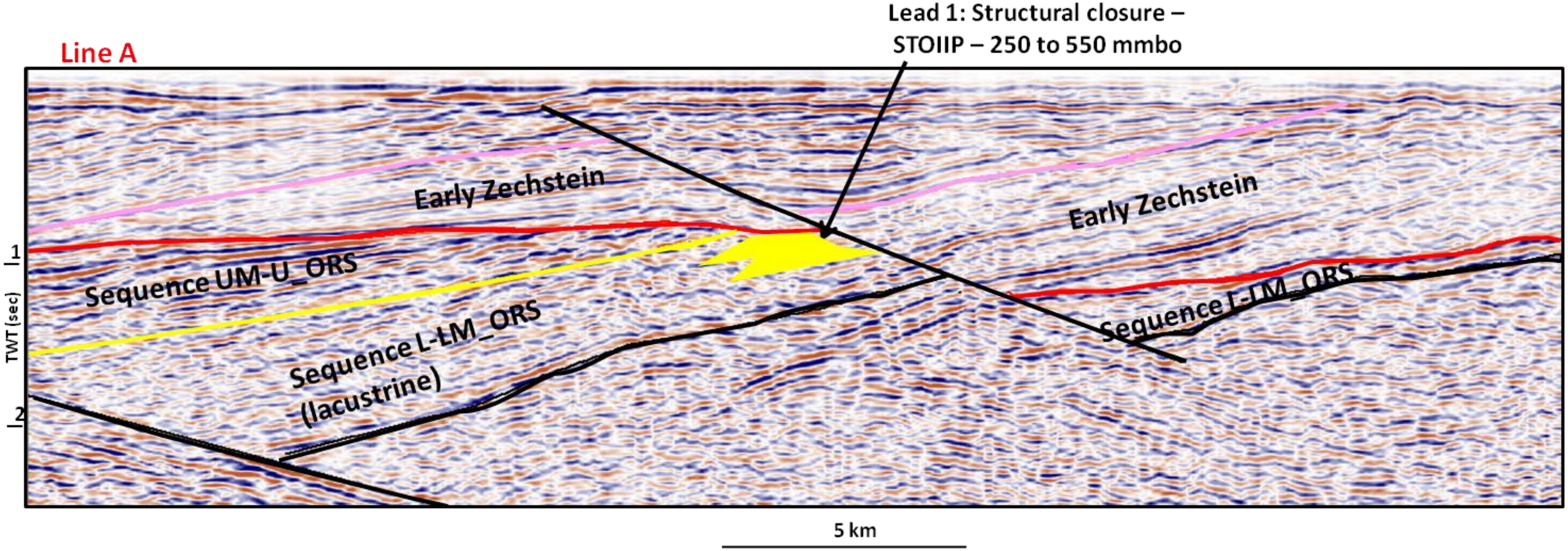


Figure 5-28. Alluvial fan reservoir intervals are hypothesized to exist within Sequence L-LM_ORS. Sequence L-LM_ORS is fault juxtaposed against the progradational Early Zechstein sequence, which may comprise sealing lithologies, because a distinct seismic facies unit (Unit 2) was recognised within the sequence in the previous chapter, and interpreted to represent mudstones and distal marine facies. If this interpretation is correct, then it gives some supporting evidence that Unit 2 facies could provide a seal. However, there is significant uncertainty in mapping the distribution of Units 2 facies across the basin, because it can only be defined confidently on two reprocessed seismic lines in the centre of the basin, and therefore it is unknown if Unit 2 facies is present across Lead 1. Note: fault seal has not been considered, due to major uncertainty in the lithology of the sequences. The location of Line A is shown in Fig 5.27.

can only be defined confidently on two reprocessed seismic lines in the centre of the basin (e.g. 4.17 and 4.18), and therefore it is unknown if Unit 2 facies is present across Lead 1.

Nevertheless, the size of the structural closure at Lead 1 (Fig 5.27 and 5.28) can be evaluated by estimating the potential volume of oil in place, which is normally defined as STOIIP (stock tank oil initially in place). The formula for STOIIP is as follows: STOIIP = GRV x conversion factor x net to gross x porosity x oil saturation x $1/B_{O.}$ GRV is the gross rock volume of the hydrocarbon bearing interval and is expressed in cubic metres. The reservoir volume can be fitted with a simple shape that allows the GRV to be calculated approximately and then the GRV is multiplied by 6.29 to convert to barrels (bbls) (Shepherd 2009).

Hydrocarbons-in-place have been calculated for the Lead 1 structural closure by using a hypothetical (full-to-spill) OWC, giving a GRV of 1680525000 m^3. The bulk volume (gross-pay-thickness) could hold up to 370 mmbo based on the following assumed reservoir parameters: 12% porosity, 50% net-to-gross, 70% oil saturation and a formation volume factor of 1.2.

5.3.1.3 Upper Middle to Upper Devonian alluvial fan play

Upper Middle to Upper Devonian rocks in the onshore areas of the WOB (e.g. Eday group: Fig 5.1) represent much drier climatic conditions in the Orcadian Basin than those that occurred in the Lower Middle Devonian (Astin 1985). The Eday Group is over 800 m thick (Fig 5.1) and composed of mainly sandstones (e.g. Fig 5.29) with a single thin discontinuous lacustrine interval (Eday Flagstone Formation) and marl interval (Eday Marl Formation) (Mykura 1976; Trewin 2002).

(a)

(b)

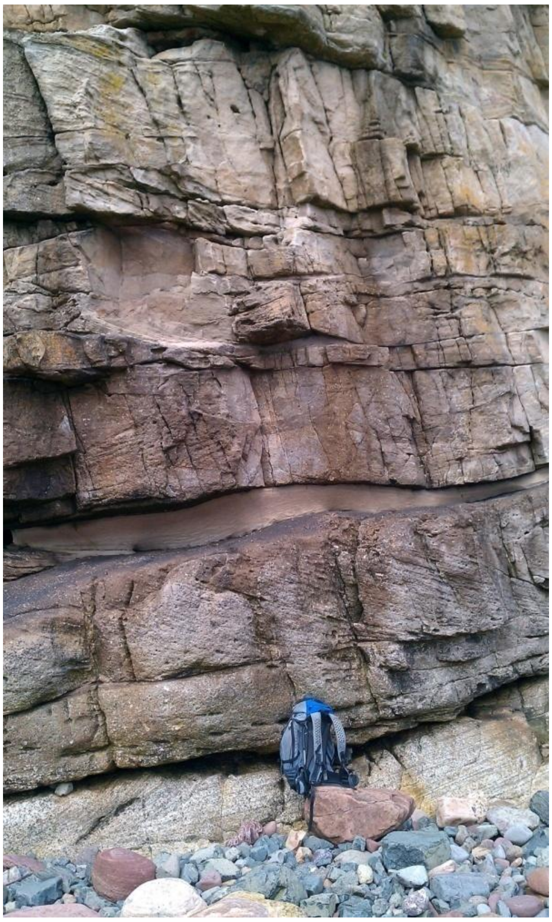


Figure 5-29. (a) GR: X330661, Y:1003587 – looking NE. Outcrop picture of bitumen residual within Lower Eday sands at Houton Head in the south of Orkney. This suggests that hydrocarbons may have been trapped in Lower Eday Sands at some point in the past. (b) GR: X319331, Y998884 – looking north. Outcrop picture of Lower Eday Sandstone Formation beds that are up to 5m thick and display cross bedding, parallel and ripple lamination. Photographs taken during field trip to Orkney.

Paleocurrent data from the Lower Eday Sandstone Formation (Owen 1994) indicates that the sands were deposited by two major fluvial systems: a larger one flowing over Caithness (NE Scotland) and the southern isles of Orkney, and a more minor system flowing from the NW over northern Orkney. The alluvial plains from these river systems merged in the East of mainland Orkney and the South Isles (Astin 1985).

The Eday sandstone is primarily yellowish red in colour and medium grained, with a few minor conglomerate units. Bedding is up to 5 m thick and displays cross bedding, parallel and ripple lamination (Fig 5.29). Deposition was mainly by fluvial processes, but also reworking of the alluvial fans by desert winds has formed aeolian intervals that accumulated against active Devonian fault scarps (Astin 1985). Owen (1994) reported that in Orkney, the sandstones have porosity of 14% to 25% and permeability of 3mD to 2000mD, which would give potentially good recovery.

Observing the tectono-stratigraphic model created for the offshore portion of the WOB in the previous chapter (refer to section 4.2), it is clear that the only potential sealing facies to reservoir rocks within Sequence UM-U_ORS is Unit 2 facies within the progradational Zechstein sequence (the major uncertainty with presence of seal in this sequence is discussed in the previous section).

Structural trapping potential for hypothetical reservoir rocks within Sequence UM-U_ORS can be evaluated with the top Sequence UM-U_ORS structural map in figure 5.30. The map illustrates a critical finding of this research study; that is, the interpreted limited distribution of Upper Middle to Upper Devonian rocks in the offshore portion of the WOB means that there are no structural closures evident that are capable of trapping hydrocarbons. Therefore, this important conclusion seriously downgrades prospectivity of plays based on Upper Middle to Upper Devonian

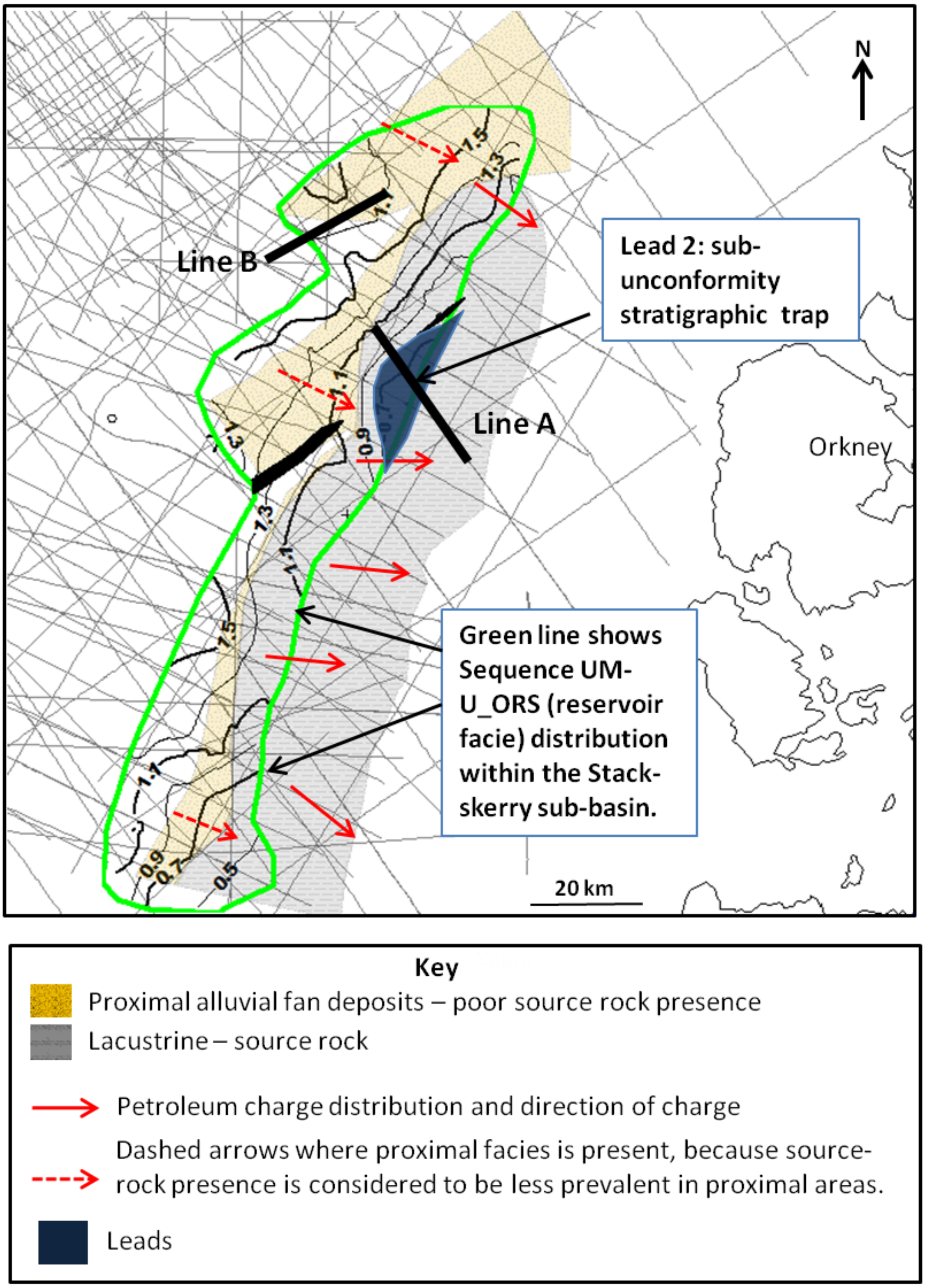


Figure 5-30. Top Sequence UM-U_ORS (reservoir facies) contoured structural map in TWTs, and Sequence UM-U_ORS source rock facies map. The figure illustrates a critical finding of this research study; that is, the interpreted limited distribution of Upper to Upper Devonian rocks in the offshore portion of the WOB means that there are no significant structural closures evident that are capable of trapping hydrocarbons - therefore, significantly downgrading prospectivity within the sequence.

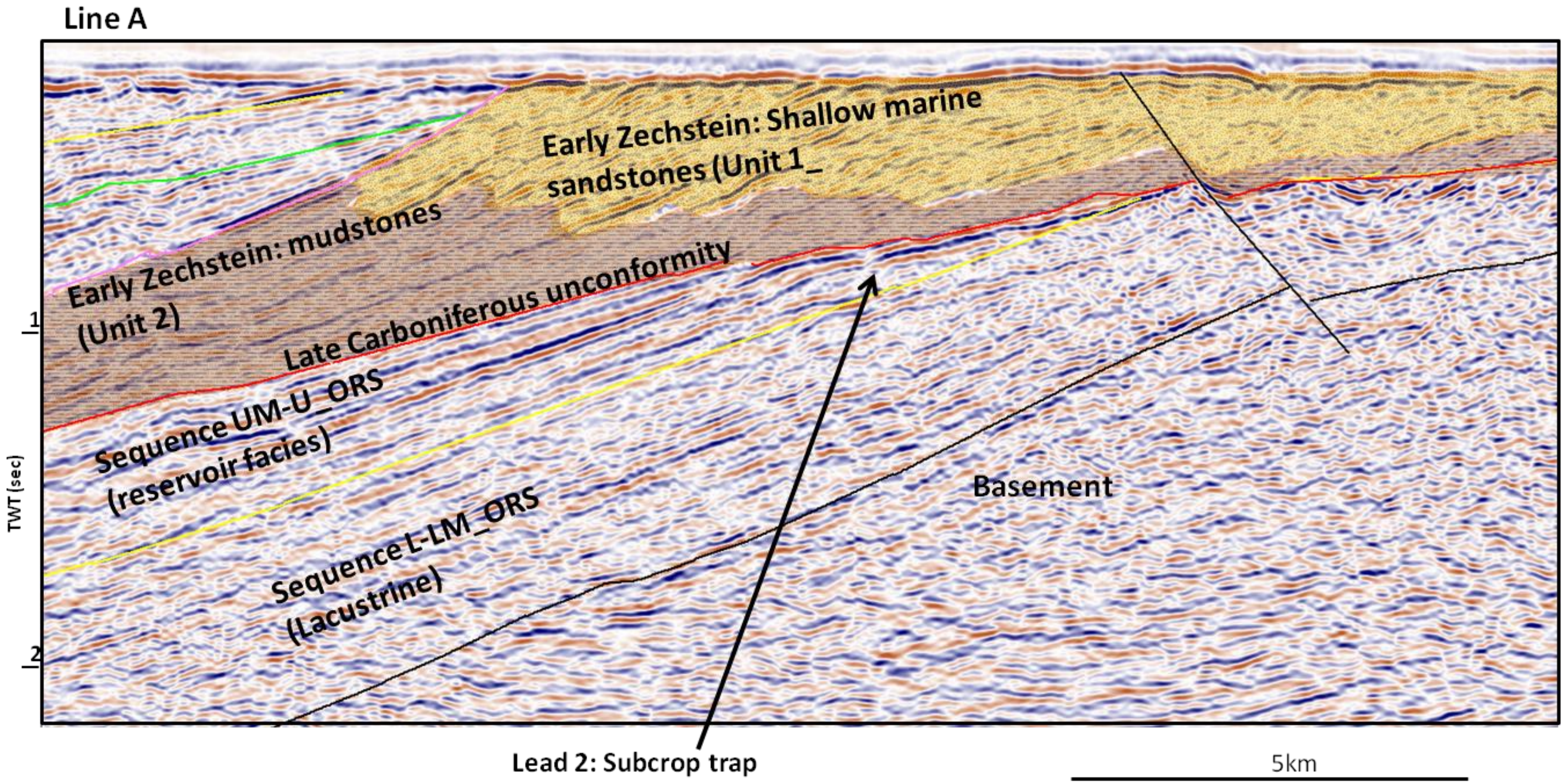


Figure 5-31. Lead 2: Sequence UM-U_ORS is truncated at the Late Carboniferous unconformity, forming a sub-unconformity stratigraphic trap (e.g. Gluyas & Swarbrick 2004). Figure 5.31 suggests the sequence structurally closes up-dip. The bottom seal to Lead 2 is postulated to be lacustrine facies within Sequence L-LM_ORS and the top seal is distal mudstone facies (Unit 2) within the Early Zechstein progradational sequence. Evidently, the main uncertainty is presence of effective seal. Location of Line A is shown in Fig 5.30.

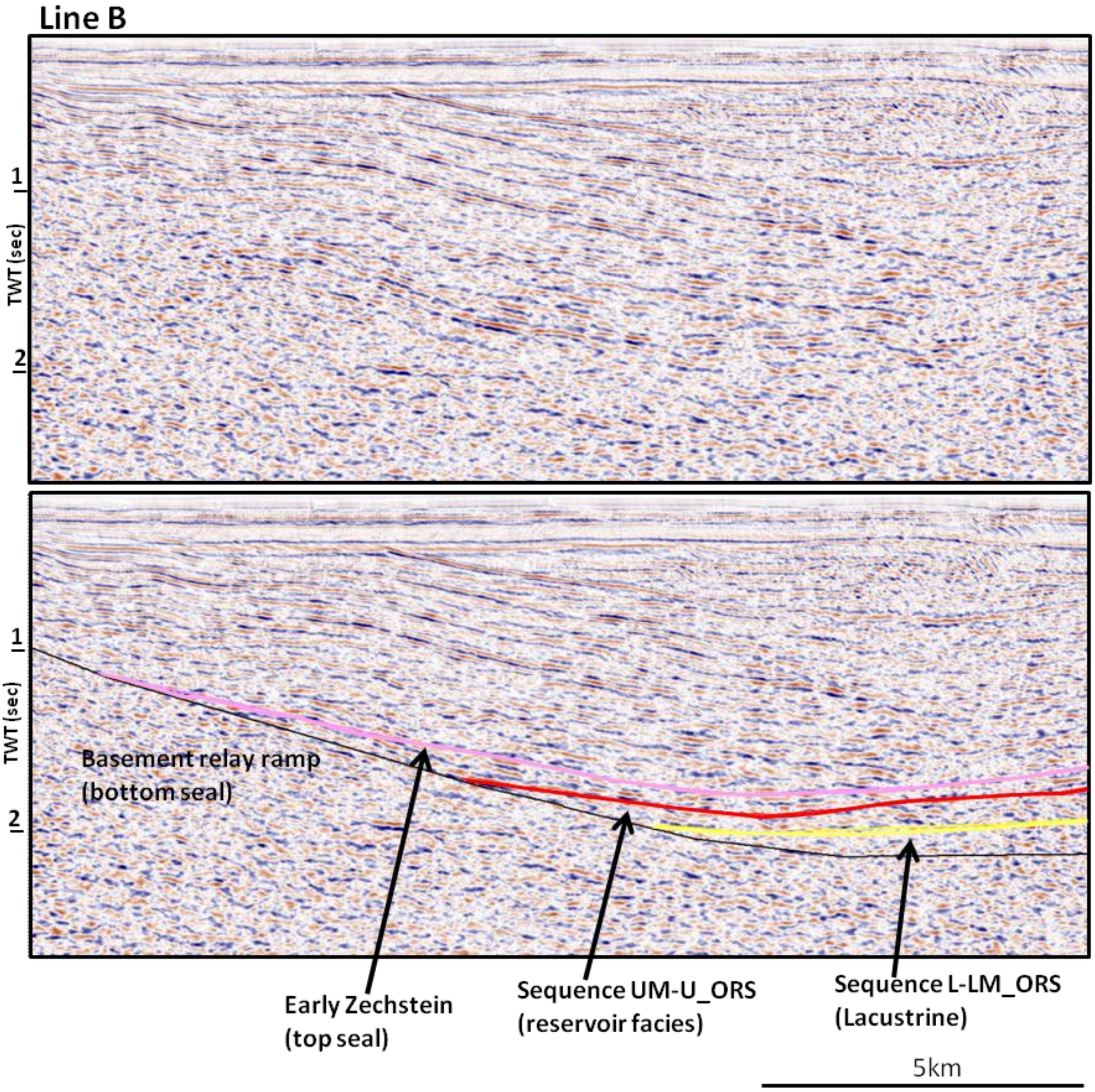


Figure 5-32. Sequence UM-U_ORS and the Early Zechstein sequence (top seal) appear to onlap a basement relay ramp (providing bottom seal) in the north of the Stack-Skerry Fault Zone. Therefore, this can be hypothesized as a stratigraphic trap. However, there is major uncertainty in the presence of seal. Additionally, it has not been possible to map up-dip stratigraphic closure of Sequence UM-U_ORS and is therefore not considered further as a lead by this study. Location of Line B is shown in Fig 5.30.

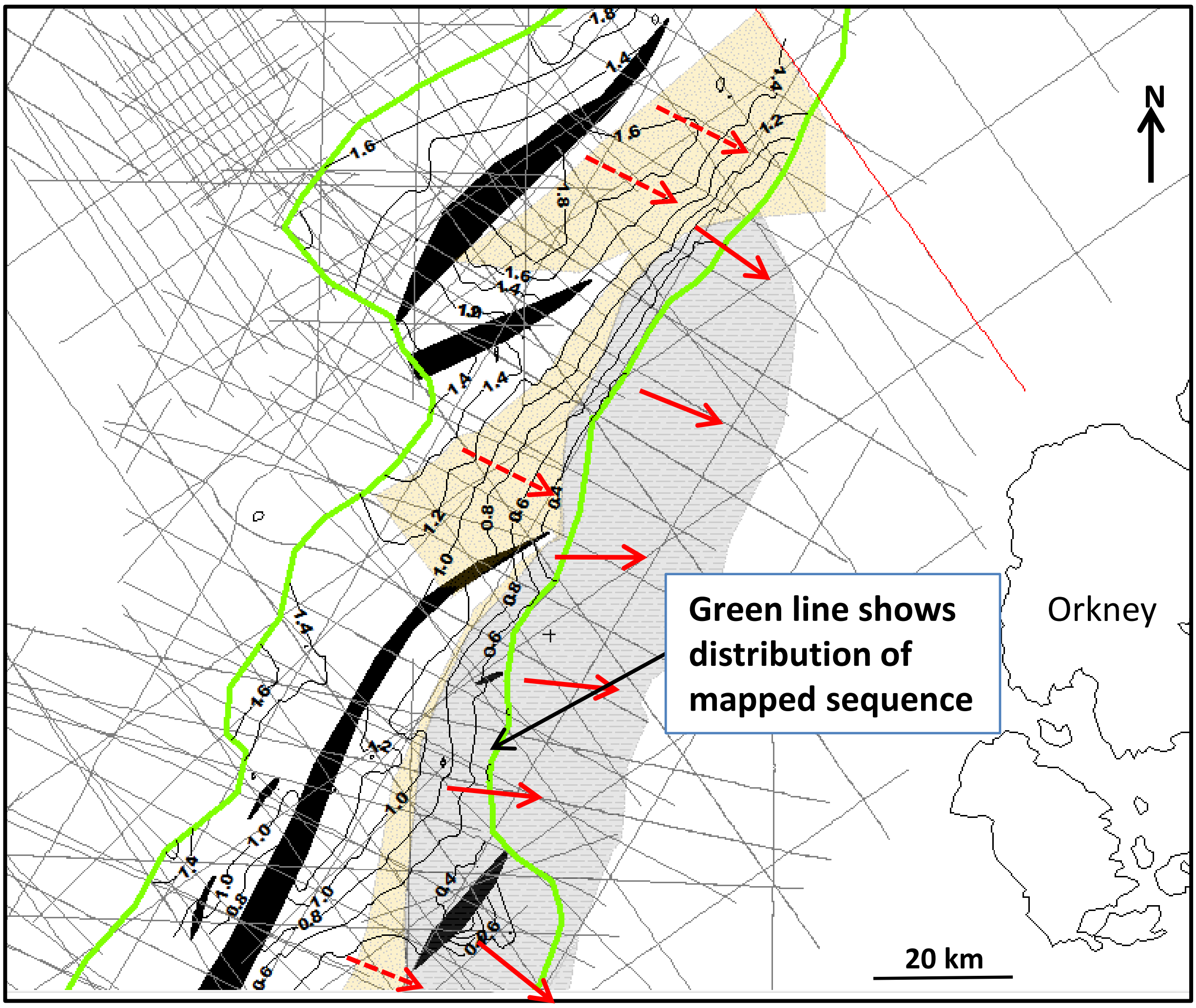
reservoir rocks, which is unfortunate, because Upper Middle to Upper Devonian rocks most likely provide the best reservoir potential in the basin (e.g. Owen 2004).

The observation that Sequence UM-U_ORS is truncated below the Late Carboniferous unconformity (Fig 5.28 and 5.31), and as a result stratigraphically pinches out up-dip towards the east in the Stack-skerry sub-basin, suggests that it may form a subcrop trap (e.g. Gluyas & Swarbrick 2004). For the trap to be viable, the sequence must structurally close up-dip. This condition can be mapped in an area in the east of the Stack-Skerry sub-basin and is labelled Lead 2 (Fig 5.30 and 5.31). Lead 2 is well situated up-dip within the petroleum charge window.

The bottom seal to Lead 2 is postulated to be lacustrine facies within Sequence L-LM_ORS and the top seal is distal mudstone facies (Unit 2) within the Early Zechstein progradational sequence, as shown on the seismic line in figure 5.31. The uncertainty of effective seal within these sequences has been discussed in detail previously.

Another type of stratigraphic trap can by hypothesized, where Sequence UM-U_ORS and the Early Zechstein sequence (top seal) appear to onlap a basement relay ramp (providing bottom seal) in the north of the Stack-skerry Fault Zone, as shown in figure 5.32. However, it is entirely unknown if the basement is capable of working as a hydrocarbon seal. Additionally, it has not been possible (data limited in resolution and quality) to map up-dip stratigraphic closure of Sequence UM-U_ORS and is therefore not considered further as a lead by this study.

For sake of argument, it is worth considering what the implications would be if the this studies interpretation of the position of Upper Middle to Upper Devonian rocks in



Key

Proximal alluvial fan deposits – poor source rock presence

Lacustrine – source rock

Petroleum charge distribution and direction of charge

Dashed arrows where proximal facies is present, because source-rock presence is considered to be less prevalent in proximal areas.

Figure 5-33. For sake of argument, this study has considered what the implications might be if this studies interpretation of the position of Upper Middle to Upper Devonian rocks in the basin is wrong (e.g. Fig 5.31), and that the interpretation given by Wilson et al. (2010) is correct (e.g. Fig 1.4). Therefore, the figure here is a structural map of Sequence P1 (Upper Devonian according to Wilson et al. (2010)). No large footwall structural closures are apparent on the 2D seismic dataset.

the basin is wrong (presented in Chapter 4), and that the interpretation given by Wilson et al. (2010) is correct (Fig 1.4). This would mean that the eastward thickening package (Sequence P1), interpreted to be a progradational Early Zechstein sequence (e.g. Fig 5.28 and 5.31) by this study (refer to 4.2.2), would actually be Upper Devonian in age. If the Wilson et al. (2010) interpretation is correct, then the Late Zechstein evaporites and mudstones that can be seen to onlap Sequence P1 (e.g. Fig 4.17 and 4.18), and are proven in the two exploration wells in the basin, could provide a seal to possible upper Devonian sands within the Sequence P1.

To evaluate prospectivity using Wilson et al (2010) interpretation, a structural map of the top of Sequence P1 (i.e. Upper Devonian reservoir facies: according to Wilson et al. 2010) is shown in figure 5.33. The map illustrates that Sequence P1 (possible reservoir facies) is preferentially distributed across footwall regions of the Stack-skerry Fault Zone, which could provide possible large structural traps. However, no footwall structural closures are apparent on the 2D seismic dataset. Additionally, Wilson et al (2010) interpreted Middle Devonian rocks (source-rock interval) to have a similar western extent within the basin as the interpretation presented in this study (Chapter 4), and therefore, even if footwall traps do exist along the Stack-Skerry Fault Zone, they would be most unlikely to have been charged adequately with hydrocarbons, as indicated by the interpreted petroleum charge direction in figure 5.33.

5.3.1.4 Zechstein prograding distal-sand play

There has been significant global exploration interest in prograding delta systems, because they commonly form prolific reservoirs for hydrocarbons (e.g. Mayall et al.

1992; Hart et al. 1997; Porebski & Steel 2003; Dixon et al. 2010). As such, the interpreted Early Zechstein progradational wedge in the WOB (refer to section 4.2.2) could provide a potential play concept in the WOB.

In the previous chapter, seismic facies analysis of Sequence P1 (interpreted to be Early Zechstein: refer to section 4.2.2 for detailed discussion) revealed that it is possible to sub-divide the sequence into two different seismic facies units, which were in turn interpreted to represent shallow marine sandstones (Unit 1), and mudstones and distal marine deposits (Unit 2) (e.g. Fig 4.17 and 4.18). It is not possible to confidently distinguish between the interpreted mudstones and distal deposits within Unit 2, on the basis of seismic facies (Fig 5.34).

By analogy to progradational systems in similar settings (e.g. Donovan 2003; Silalahi et al. 2009), it is plausible that turbiditic channel and fan deposits (e.g. Fig 5.35) could occur in the slope to distal areas of the clinoforms and provide excellent reservoir targets. If present, the sand bodies could be situated within slope and basinal mudstones facies interpreted in Unit 2, which may provide a seal.

Turbidites form important play types in many parts of the world, including the Gulf of Mexico (e.g. McGee et al. 1993) and the Tertiary of the UKCS (e.g. Newman et al. 1993; Gardiner 2006). A classic regional setting for such a trap involves lateral pinch-out of sand facies at the margin of channel deposition. However, pure stratigraphic traps are relatively rare, as some degree of structural closure is often evident (Allan et al. 2006).

Possible distal basin floor fans within the Early Zechstein sequence could be located on the foot-wall region of the Stack-Skerry Fault Zone (5.17 and 5.34), giving the potential for structural trapping mechanisms. Onlap of Late Zechstein mudstones and

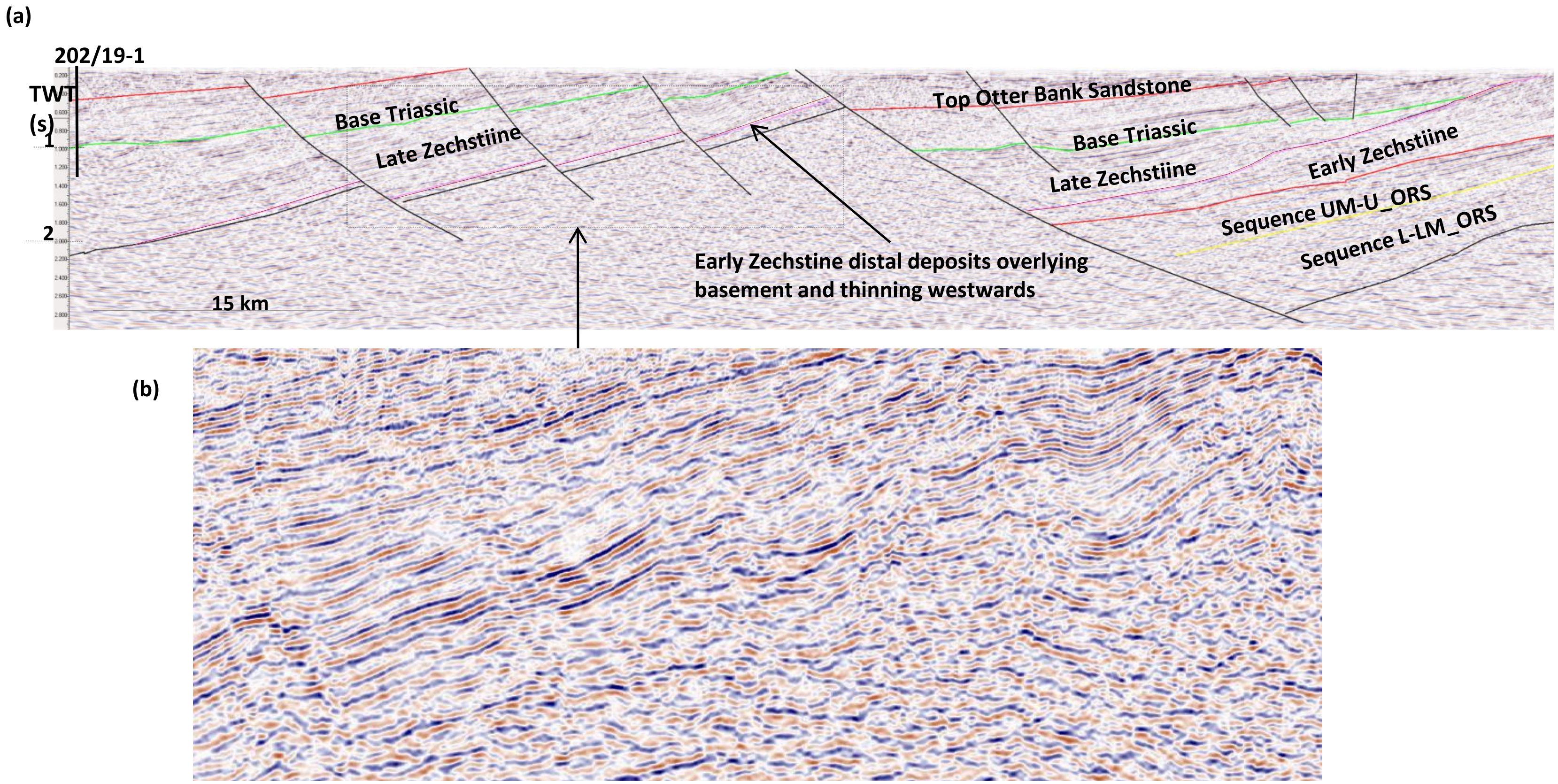


Figure 5-34. (a) Interpretation of part seismic line 2 – for location see Fig 4.3. (b) Enlargement of area shown in black box in (a), which shows that it is not possible to confidently distinguish between the interpreted mudstones and distal deposits within Unit 2 of the Early Zechstein prograde (Unit 2 shown in Fig 4.17 and 4.18), on the basis of seismic facies.

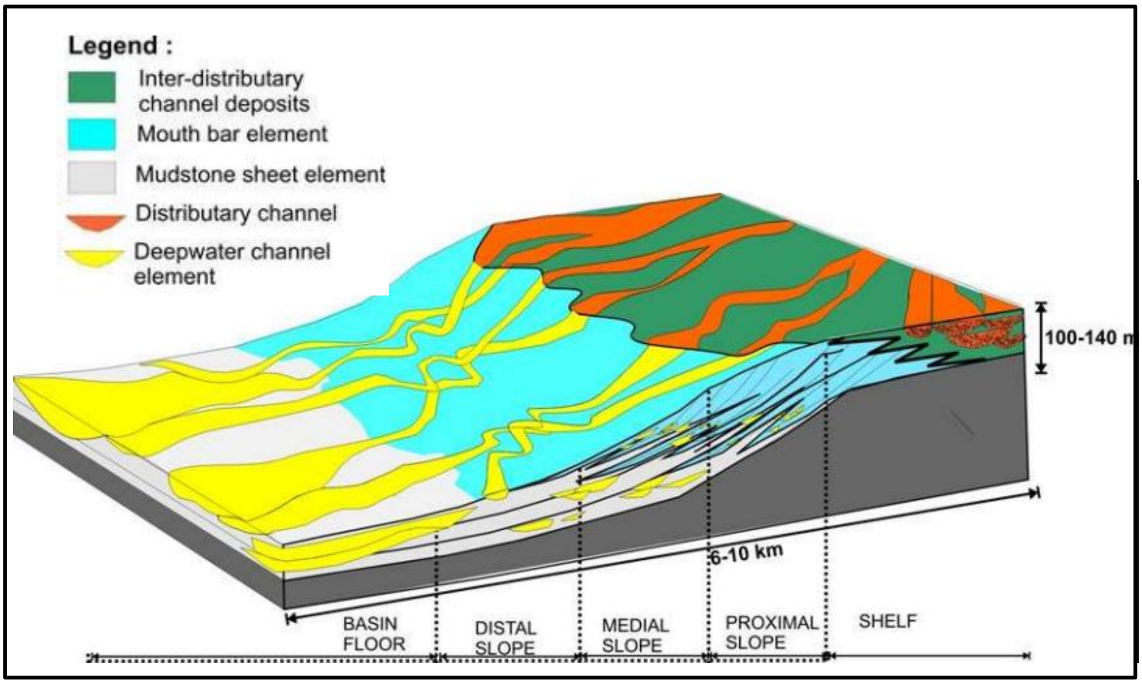


Figure 5-35. Analogue prograding delta system from Silalahi (2009) - to show possible characteristic facies distributions that may be expected within the Early Zechstein progradational sequence within the WOB. The block block diagram illustrates proximal to distal stratigraphy changes in the Sobrarbe Formation, within the prograding shelf-slope-basin of the onshore Pyrenees.

evaporites onto the prograding sequence could give a top seal to the sand bodies (e.g. 5.34). However, the structural map of the top the Early Zechstein sequence (i.e. top Sequence P1) in figure 5.33 illustrates that there is no significant structural closures at the seismic scale. Furthermore, figure 5.33 also exemplifies that the footwall to the Stack-Skerry Fault Zone is possibly outside the main petroleum charge window.

An Early Zechstein play in the WOB is speculative, at best, due to the major uncertainty in presence of reservoir and seal facies. No significant leads have been identified that may give a structural component to traps and that are capable of being charged. Therefore, an Early Zechstein play is not considered further.

5.3.1.5 Triassic fluvial sand play

The Strathmore Field, located in the Faroe-Shetland Basin, consists of dipping Triassic sandstones truncated beneath a broad structural closure at base Late Jurassic level (Fig 5.36). The truncated Triassic, which is over 10000 ft thick down-dip, consists entirely of sandstone, but only the lowest, quartz-rich, 550 ft thick Otter Bank Sandstone is considered reservoir quality. The overlying Foula Sandstone has a similar grain size and depositional setting to the Otter Bank Sandstone, but its immature detrital mineralogy has resulted in early compactional porosity loss, making the unit an effective top seal to the Otter Bank Sandstone reservoir (Herries et al. 1999).

The significance of the Strathmore Field to this study is that a comparison can be made between the Triassic sequence in the Strathmore Field and the Triassic rocks encountered in WOB well 202/19-1 of the WOB, in order to assess the potential for a Strathmore play-type in the WOB.

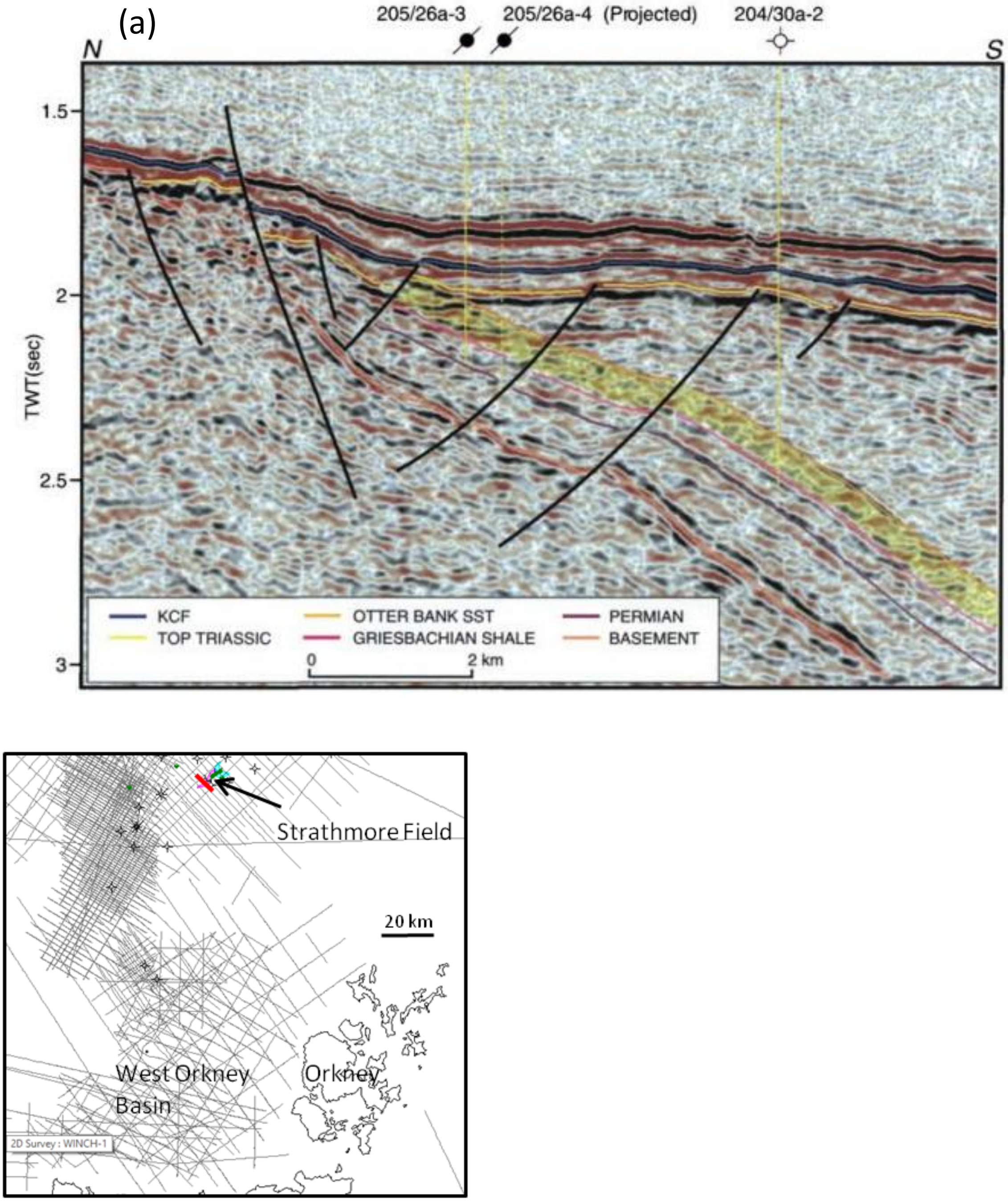


Figure 5-36. (a) North-south seismic dip section through Strathmore Field showing the dipping slab of Lower Triassic Otter Bank Sandstone reservoir, shaded yellow (from (Herries et al. 1999), and (b) location map of the Strathmore Field, with red line showing location of seismic line in (a).

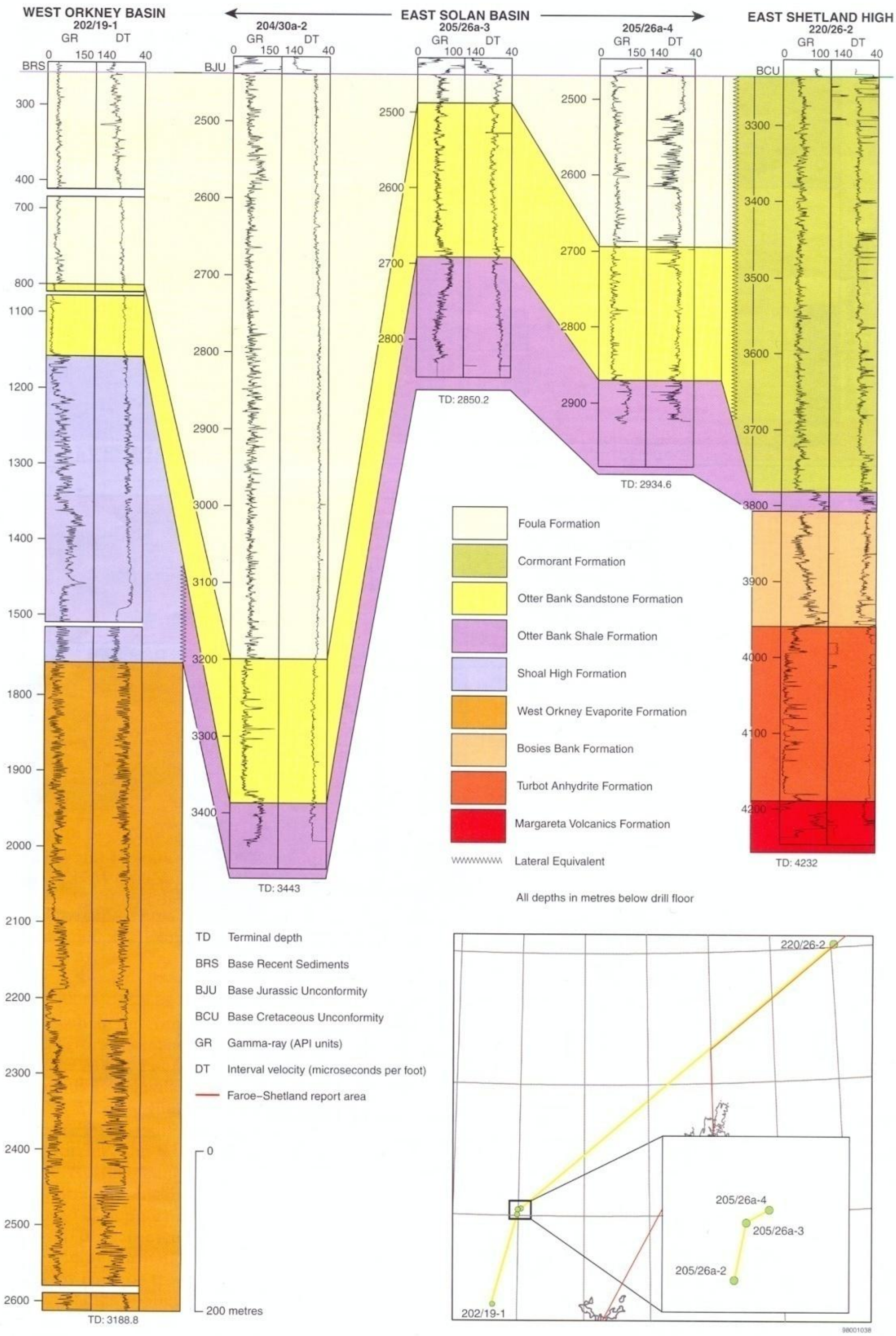


Figure 5-37. Well log correlation of Permo-Triassic rocks between the WOB (well 202/19-1) and the Faroe-Shetland Basin - correlation is based only on lithology and wire-line log signature (from Ritchie et al. 2011).

Attempts have been made to correlate well penetrations of Triassic rocks in the Faroe-Shetland Basin and the WOB, being based on lithology and wire-line log response (Ritchie et al. 2011). However, it should be stressed that there is an absence of fauna and flora within Triassic rocks, and thus correlations should be treated with extreme caution.

Nonetheless, the lower 598 m of the Triassic succession in WOB well 202/19-1 has been correlated to the Shoal High Formation of the Faroe-Shetland Basin on the basis of lithology and wireline log response (Fig 5.37). It consists of inter-bedded mudstones, siltstones and sandstones. Individual beds can be up to 80 m thick. The sandstone beds are fine to very fine grained and moderately well-sorted. Therefore, this interval is considered to have poor to moderate reservoir quality.

The Shoal High Formation is overlain by 902 m of the equivalent (Ritchie et al. 2011) Otter Bank Sandstone (reservoir in the Strathmore field) and Foula (seal in the Strathmore Field) Formations. They mainly comprise sandstone, that grades in places to conglomerates with sporadic thin calcareous siltstone and silty mudstone. Similarly to the Strathmore Field, the boundary between the Otter Bank Sandstone and Foula Formations is taken at a major increase in the gamma-ray log signature (Fig 5.37) (Ritchie et al. 2011).

From the above, it appears that a Triassic sandstone interval in the WOB appears lithologically similar to the prospective Otter Bank Sandstone (reservoir) and Foula (seal) Formations of the Strathmore Field. Therefore, a Strathmore play-concept could potentially be applied to the WOB. However, seismic mapping (Fig 5.34) of the top Otter Bank Sandstone Formation, from WOB well 202/19-1, across the WOB, indicates that it is very shallow within the section (above 0.5s TWT), and thus any potential Otter Bank reservoir in the WOB would likely be subject to biodegradation.

5.4 Summary and conclusion

Orcadian Basin rift topography and its effect on lake size and distribution across the rift-system is currently very poorly understood (e.g. Rogers & Astin 1991). This study, by the integration of seismic and paleocurrent data (e.g. Figs 5.6, 5.7 and 5.8), has demonstrated that in the WOB region of the Orcadian Basin, rift topography had a major control on Lower Middle Devonian depositional drainage patterns; which can be characterised as axial through-going drainage (e.g. Leeder & Gawthorpe 1987). This is similar to other continental depositional models proposed for similar settings such as Greece (Collier & Gawthorpe 1995) and Karoo rift basins of Zambia (e.g. Banks et al. 1995) and conceptual models for continental rift basins (e.g. Fig 5.9: Gawthorpe & Leeder 2000).

The implications of this on possible source-rock distribution is that as well as large vertical variations in TOC, attributed to lake level changes, significant lateral variations in source-rock TOC will also be expected, due to local footwall sourced and axial-flow alluvial fans propagating into the half-graben sub-basins and diluting organic content. TOC content and source-rock quality will probably best be preserved in central areas of the Stack-Skerry sub-basin, away from the main alluvial fan channel systems, such as relay zones. The source-rock GDE model (Fig 5.15) for the Lower Middle Devonian presented, may be applied to others areas of the Orcadian Basin, in order to help evaluate plays based on the presence of a Devonian source-rock.

Perhaps one of the major attractions for hydrocarbon exploration in the WOB is the observation that Lower Devonian aeolian sandstones outcrop onshore at Orkney and contain bitumen residual. However, the discontinuous and localised distribution of the Lower Devonian aeolian sandstones onshore, suggests that it is an exceptionally high-risk play concept to locate in the offshore potion of a WOB, as the majority of Lower Devonian rocks is composed of conglomeratic mudstones and therefore considered non-reservoir potential. There was no apparent evidence on seismic for Lower Devonian aeolian sandstones being present offshore, but this is most likely due to the resolution and quality of the 2D seismic dataset, and a lack of appropriate well control.

A lower Devonian aeolian sandstone play would rely on Lower Middle Devonian lacustrine rocks acting as a seal. Other than the possibility that hydrocarbons may have once been trapped at Yesnaby (e.g. Marshall & Hewett 2003), the sealing capacity of the Lower Middle Devonian lacustrine sequence is largely unknown, and is notoriously difficult to predict (e.g. Cartwright et al. 2007). Nonetheless, the sequence is highly fractured, with a high sand content (e.g. Fig 5.2 and 5.4), and thus, seal integrity is considered very high risk.

With analogy to the Inner Moray Firth, reservoir thick alluvial fan intervals may exist within the Lower Middle Devonian lacustrine sequence in the WOB. The Lower Middle Devonian GDE model in figure 5.15 can be used speculatively to facilitate prediction of the main alluvial fan channel systems and therefore the most likely locations to create inter-fingering of sandstone (reservoir) and lacustrine (source and seal) facies within the basin, as shown in figure 5.24. Relay zones within the Stack-Skerry Fault Zone most likely provided the main channel systems for alluvial fan deposition into the Stack-Skerry sub-basin, and thus the largest alluvial fans can be postulated to have accessed the Stack-Skerry sub-basin via such structures. Footwall sourced fans may be better positioned to form up-dip pinch-out traps, than axial and hanging-wall sourced fans. Nonetheless, intra-lacustrine stratigraphic traps are considered very high risk due to presence of effective trap.

The existence of Lower Middle Devonian combination stratigraphic-structural and pure structural traps is possible. Footwall structural closure can only be mapped at one location in the south of the basin (Lead 1: Fig 5.27 and 5.28). Hydrocarbons-in-place have been calculated for the Lead 1 structural closure, which is estimated to be 200 to 500 mmbo. The major risk with Lead 1 is presence of seal in the Early Zechstein sequence.

A critical finding of this research study is that the interpreted limited distribution of Upper Middle to Upper Devonian rocks in the offshore portion of the WOB means that there are no significant structural closures evident that are capable of trapping hydrocarbons. Therefore, this seriously downgrades prospectivity of plays based on Upper Middle to Upper Devonian reservoir rocks, because onshore studies have shown this interval to provide the best reservoir potential in the Orcadian Basin (e.g. Owen 1994). There is only the potential for a subcrop trap, where Upper Middle to Upper Devonian rocks are truncated and pinch-out at the Late Carboniferous unconformity identified on seismic (Fig 5.30 and 5.31). A region where up-dip stratigraphic pinch-out and closure of the interpreted Upper Middle to Upper Devonian sequence in the basin has been mapped (Lead 2). Lead 2 is well situated within the petroleum charge drainage area. The major risk with Lead 2 is the presence of effective sealing facies within the interpreted Early Zechstein sequence in the basin.

An Early Zechstein marine turbiditic sandstone play can be hypothesized, based on analogues to progradational systems in similar settings (e.g. Donovan 2003; Silalahi 2009: Fig 5.35). No structural closures were apparent and therefore this play concept would rely on stratigraphic trapping mechanisms. Thus, the major risks are presence of trap, seal and reservoir.

A Strathmore Field play-type in the WOB was evaluated and shown to be compromised by the shallow and limited distribution of the proposed reservoir interval (Otter Bank Sandstone: Fig 5.34, 5.36 and 5.37), which is potentially outside the petroleum charge drainage area, and even it was charged, any trapped hydrocarbons would be subject to biodegradation.

Chapter 6

6 Discussion: Implications for Hydrocarbon Exploration

6.1 Introduction

Hydrocarbon prospectivity of the WOB was severely downgraded in the 1980s to early1990s, due to the drilling of two dry wells in the basin and superior exploration opportunities elsewhere at the time, such as the West of Shetlands, and Central and North Sea. As a result, the WOB has been largely ignored by industry until recent years.

The petroleum potential of the WOB is largely unknown, because of poor understanding on the structural and stratigraphic development of the basin. A major component of this research study has been to evaluate the geological framework of this frontier region. This work (i.e. Chapters 3, 4 and 5) is integrated into a basin model in the chapter, in order to assess prospectivity for Premier Oil (the sponsor of this research project), who are the current operators present in the basin.

The timing of hydrocarbon generation in the WOB was evaluated for two pseudo wells (A and B) with industry standard 1D basin modelling software (Genesis) from Zetaware, Inc. In Chapters 4 and 5, it was suggested that Devonian source-rocks may be present within the Stack-Skerry sub-basin. Therefore, Pseudo well A is situated in the deeper region of the Stack-Skerry sub-basin and Pseudo-well B is located towards a shallower location, as shown on the seismic line in figure 6.1.

In basin modelling the conceptual model represents a simplified illustration of the geological development of a basin and is therefore based on the geological framework of the study area. It provides the temporal basis required to input and simulate source-rock maturation (Welte & Yükler 1981; Welte & Yalçin1988; Poelchau et al. 1997). The reappraisal of the tectono-stratigraphic framework of the WOB, presented in the previous chapters, provides the most important input into the 1D conceptual basin model (e.g. Underdown & Redfern 2007). It is used directly to constrain the sedimentation history of the basin, by subdividing it into a continuous series of events, each with a specified age and duration. Each stratigraphic event represents a time span during which sediment deposition and non-deposition (hiatus) or uplift and erosion is suggested to have occurred.

However, it is apparent from the previous chapters that there is major uncertainty in constraining the structural and stratigraphic development of the WOB, due to the lack of well control and low density of seismic, and that the basin has experienced prolonged and multiple uplift and erosional events, that has resulted in no post-Triassic section being preserved in the basin.

Tables 6.1 to 6.5 illustrate all the parameters that were used to constrain the Genesis model (refer to Appendix 1 for an overview on the basin modelling principles that is used by the Genesis software). Due to the massive uncertainty in the data presented here, a possible range of values for each individual parameter are shown in the tables. The mean value for each range was input into the model.

Tables 6.1 and 6.2 illustrate the thickness of the sequences encountered in Pseudo Wells A and B respectively, and also their interpreted age and lithology. Uncertainty in the velocity information required to depth convert each sequence from the seismic line in figure 6.1 has a significant impact on modelling the burial history of the basin and predicting source-rock maturation. For example, an over predicted sedimentary thickness overlying the modelled source-rock would consequently give a higher level of source-rock maturation, and vice-versa. Additionally, uncertainty in the lithology of each sequence not only influences the predicted thermal conductivity of the sediment (refer to Appendix 1), but also how the rock is modelled for decompaction.

A significant task in Chapter 4 was to establish the amount of eroded section at each interpreted erosional event within the basin, and whether there had been any significant post-Triassic rifting and deposition within the basin. Where such large-scale erosion is interpreted to have occurred in a basin, the prediction of the thickness and the lithology of the eroded sediments is a crucial parameter in basin modelling, as this significantly impacts predicting the timing of source-rock maturation (e.g. Hantschel & Kauerauf 2009).

A Late Carboniferous to Early Permian (Variscan) unconformity was interpreted on 2D seismic in the WOB, with estimated (from restoring the eroded section) removal of perhaps 100s to 1000s of metres of Upper Devonian and Lower Carboniferous sediments (Tables 6.3 and 6.4). The massive uncertainty in the magnitude of Late Carboniferous uplift and erosion in the basin has significant implications for the modelled volume of source-rock capable of generating hydrocarbons during reburial in the Late Permian to Early Jurassic. For example, lowering the modelled mean estimated value (0.75 km: Table 6.3) of removed section at the Late Carboniferous unconformity would result in a decrease in the modelled thickness of the original Devonian succession overlying the source rock.

Additionally, there is major uncertainty in the extent and magnitude of post-Triassic erosional and depositional events, due to the lack of preservation of rocks younger than Triassic in basin. Nonetheless, an attempt was made to reduce some of this uncertainty in Chapter 4, by synthesizing published regional AFTA (e.g. Holford et al. 2010) with the results obtained (this study) from extensive seismic mapping in the basins to the immediate northwest of the WOB (Rona, Solan and Papa Basins), where there are Mesozoic and Tertiary sediments preserved. The results from this work suggested that the WOB likely experienced post-Triassic exhumation events in the

Mid-Jurassic to Early Cretaceous and Cenozoic, with an estimated present-day net-thickness of removed section being 2.7 to 3.7 km. It is conceivable that 0.5 to 1 km of sediments were deposited across the WOB during regional subsidence in the Late Cretaceous. This may indicate that about 2 to 3 km of Triassic to Early Jurassic sediments have been eroded from the WOB (Table 6.4).

Source rock kinetic reactions, such as kerogen to oil and gas conversion, is a function of kerogen type, temperature and time. Higher temperature results in faster reaction (Durand & Monin 1980). It is possible to evaluate the extent of the reaction from the transformation ratio, which is defined as the ratio of generated petroleum to potential petroleum in a source rock. If it is plotted against geological time, then the timing of hydrocarbon generation may be inferred (Tegelaar & Noble 1994).

The kinetic parameters required to model source-rock transformation ratio include: kerogen lithofacies, initial HI (hydrogen index) and TOC (total organic carbon content). As these parameters are unknown for the Lower to Lower Middle Devonian interval, a specific built-in tool within Genesis is used for standardised playa/shallow lacustrine oil-prone shales that have initial values of 500 HI and 5% TOC (Tables 6.1 and 6.2). This seems appropriate; because Marshall and Hewett (2003) report that elsewhere in the Orcadian Basin, the succession shows a preponderance of oil-prone type I and II kerogen.

Genesis 1D basin-modelling-software solves for crustal temperature, from given heat flow and thermal conductivity. Thermal conductivity is assumed for each defined lithology and is a function of compaction (Makowitz et al. 2006; Anyiam & Onuoha 2013). However, heat flow through geological time of the WOB is a major uncertainty in this study. In general, rift basins are subject to variable and relatively high heat flows (McKenzie 1978; Pollack et al. 1993). For example, present day thermal gradients in Tertiary rocks within the Rhine rift graben range between 40 and 90 °C/km (Robert 1985).

High heat flows during formation of the Orcadian rift Basin seem likely; considering that rifting was also accompanied with widespread Devonian volcanism (e.g. Astin 1990; Trewin 2002). Within the Inner Moray Firth region of the Orcadian Basin, Green et al. (1995) conducted apatite-fission-track-analysis (AFTA) on a single well (Well UK 12/16-1) and estimated a Late Carboniferous geothermal gradient of 57 °C/km.

A second major phase of rifting in the WOB, interpreted to have occurred in the Late Permian to Early Jurassic (refer to section 4.2), was most likely also characterised by high geothermal gradients. Appetite fission track data from the Faroe-Shetland Basin (which experienced Permo-Triassic rifting e.g. Dean et al. (1999)) suggests that Late Permian to Early Triassic geothermal gradients were about 40 °C/km (Mark et al. 2008).

Following major Late Permian to Early Jurassic rifting, geothermal gradients would have most likely declined in the WOB (e.g. McKenzie 1978). Holford et al. (2010) carried out AFTA on WOB well 202/19-1 and estimated that Early Cretaceous and Cenozoic geothermal gradients were similar to the present day value of 25.3 °C/km.

Thus, due to the major uncertainty in the thermal history of this complex heavily-exhumed poly-phase rift basin, three crustal thermal cases (low, medium and high geothermal gradients) for the two main rift events in the basin (Devonian and Late Permian to Early Jurassic) where modelled (Table 6.5); with inferred geothermal gradients of 45 °C/km and 30 °C/km (low case), 60 °C/km and 40 °C/km (medium case), and 75 °C/km and 50 °C/km (high case) for the Devonian and Late Permian to Early Jurassic rift events respectively. The Cretaceous to Cenozoic was kept at a constant value of 25.3 °C/km (based on Holford et al. 2010).

6.2 Implications for prospectivity

The plots of burial history versus source-rock transformation ratio for the three different inferred thermal cases in figures 6.2 to 6.4, indicate that only significant hydrocarbon generation occurs during reburial in the Late Permian to Early Jurassic when assuming low to mid-case geothermal gradients (Fig 6.2 and 6.3). Nonetheless, for the WOB to be considered prospective, generated hydrocarbons would have needed to become and remained trapped during rifting, in rift-related structural and stratigraphic traps (refer to Chapter 5), and survived multiple and prolonged uplift events since the Mid-Jurassic (Fig 6.2 to 6.4). Thus, the main risks with petroleum exploration in the WOB are proposed to be breaching of traps and seal performance.

Where tectonic deformation of a basin occurs post-emplacement of hydrocarbons, there is an increased risk of tectonic breaching and cap-rock leakage (e.g. Underhill 1991; MacGregor 1995; Dore et al. 2002; Cavanagh et al. 2005; Ohm et al. 2008). There is a high probability that the continuation of post hydrocarbon-generation rifting in the WOB during the Triassic to Early Jurassic, resulted in trap failure. This could have been facilitated by both seismic and sub-seismic scale cross-fault juxtaposition of reservoirs from different stratigraphic levels or through the creation of a connected system of juxtaposed leaky beds through the cap-rock interval. Clearly, any petroleum play-concept associated with the Lower Middle lacustrine acting as a

Table 6.1 – Pseudo Well A

Sequence	Interpreted age	Interpreted lithology	Range of Interval velocities used (m/s)	Time thickness (seconds)	Pseudo Well A Thickness range (km)	Pseudo Well A modelled thickness (km)	Modelled source-rock kinematic values from Marshall & Hewett (2003)
1	Lower to Lower Middle ORS	mainly lacustrine	4500 - 5500	0.27	1.215 – 1.485	1.35	lacustrine oil-prone shales - initial values of 500 HI and 5% TOC
2	Upper Middle to Upper ORS	mainly alluvial sandstone	3900 - 4900	0.16	0.620 – 0.779	0.7	
3	Late Permian (Early Zechstein)	mainly clastics – sandstone, mudstone	3500 - 4500	0.27	0.936 – 1.204	1.07	
4	Late Permian (Late Zechstein)	halite, mudstone, sandstone	3500 - 4500	0.06	0.192 – 0.270	0.220	
5	Triassic		3000 - 4000	0.23	0.686 – 0.920	0.8	

Table 6.2 – Pseudo Well B

Sequence	Interpreted age	Interpreted lithology	Interval velocity used (m/s)	Time thickness (seconds)	Pseudo Well B Thickness range (km)	Pseudo Well B Modelled thickness (km)	Modelled source-rock kinematic values from Marshall & Hewett (2003)
1	Lower to Lower Middle ORS	mainly lacustrine	4500 - 5500	0.19	855 - 1045	0.950	lacustrine oil-prone shales - initial values of 500 HI and 5% TOC
3	Late Permian (Early Zechstein)	mainly clastics – sandstone, mudstone	3500 - 4500	0.24	840 - 1080	0.970	

Table 6.3 – Age and amount eroded at unconformities

Interpreted age of unconformities	Interpreted range of possible eroded section	Modelled eroded section
Late Carboniferous to Early Permian	100s – 1000s metres	0.75 km
Mid Jurassic to Early Cretaceous	1.5 - 2 km	1.75 km
Cenozoic	1.2 – 1.7 km	1.45 km

Table 6.4 – Age and thickness of additional section

Interpreted age of additional section, that has subsequently been eroded	Interpreted thickness range of additional section, that has subsequently been eroded	Modelled thickness of additional section, that has subsequently been eroded (km)
Late Devonian to Early Carboniferous	100s – 1000s metres	0.75
Late Triassic to Early Jurassic	2 – 3 km	2.5
Late Cretaceous	0.5 – 1 km	0.75

Table 6.5 – Geothermal gradients

Time	Geothermal gradient °C/km - Low case	Geothermal gradient °C/km - Mid case	Geothermal gradient °C/km - High case
Devonian	45	60	75
Late Permian to Early Jurassic	30	40	50
Cretaceous – present day	25.3	25.3	25.3

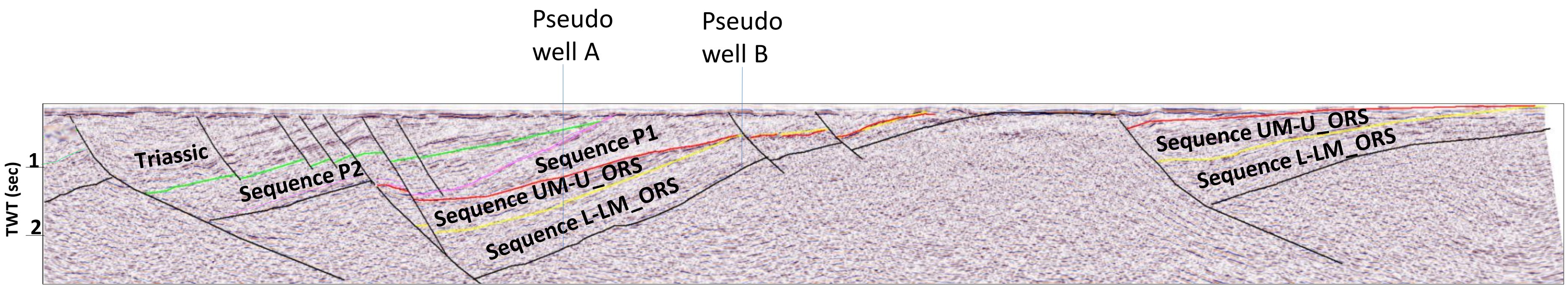


Figure 6-1. Seismic line showing location of pseudo well A and B in the Stack-Skerry sub-basin. For location see Line 1 in figure 4.1.

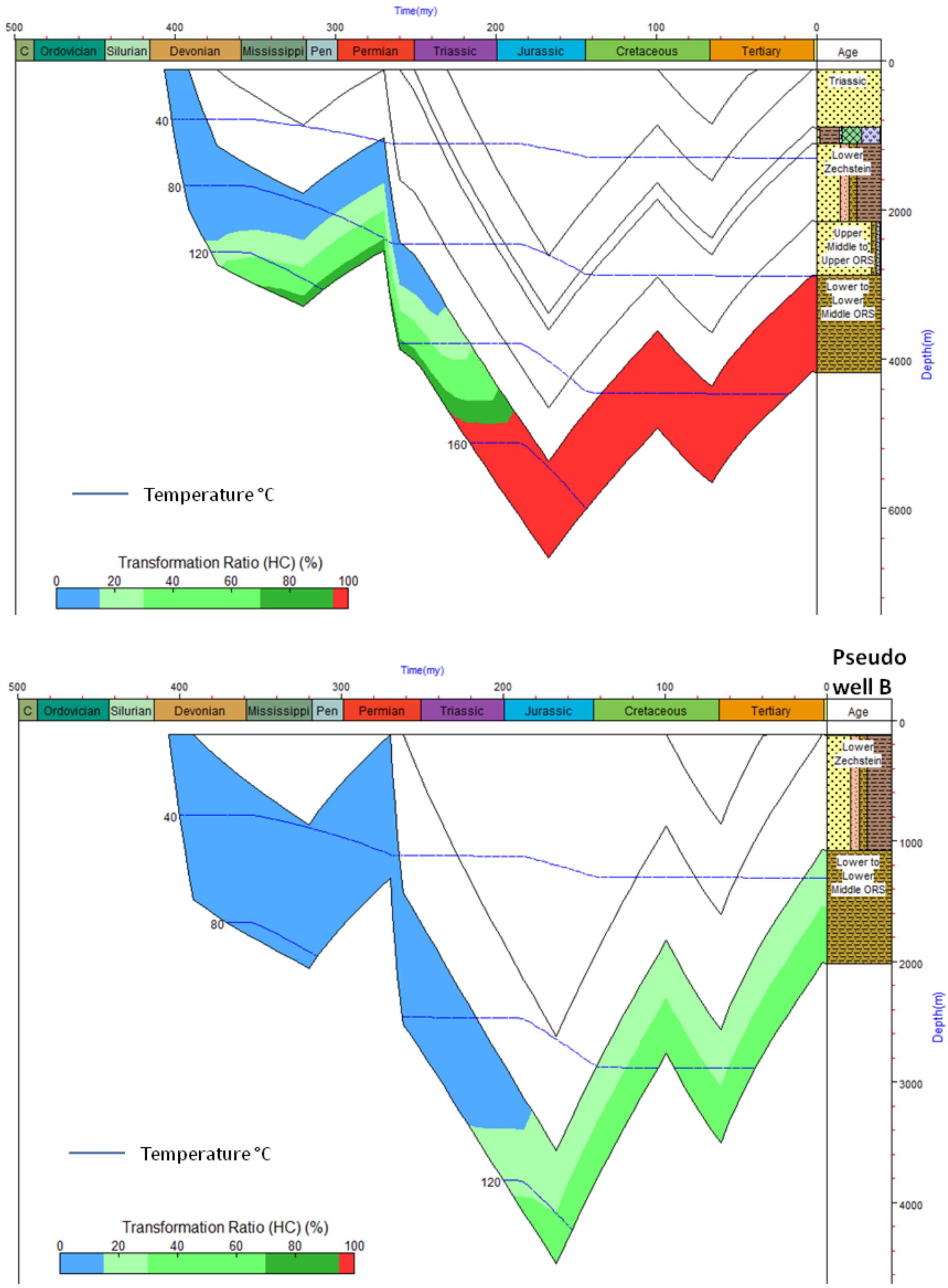


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Figure 6-2. Genesis 1D basin model for a low thermal case in the WOB, using inferred geothermal gradients of 45 °C/km and 30 °C/km for the Devonian and Zechstein to Early Jurassic rift events respectively. The Cretaceous to Cenozoic was kept at a constant value of 25.3 °C/km (based on Holford et al. 2010). Location of pseudo wells A and B is shown in figure 6.1

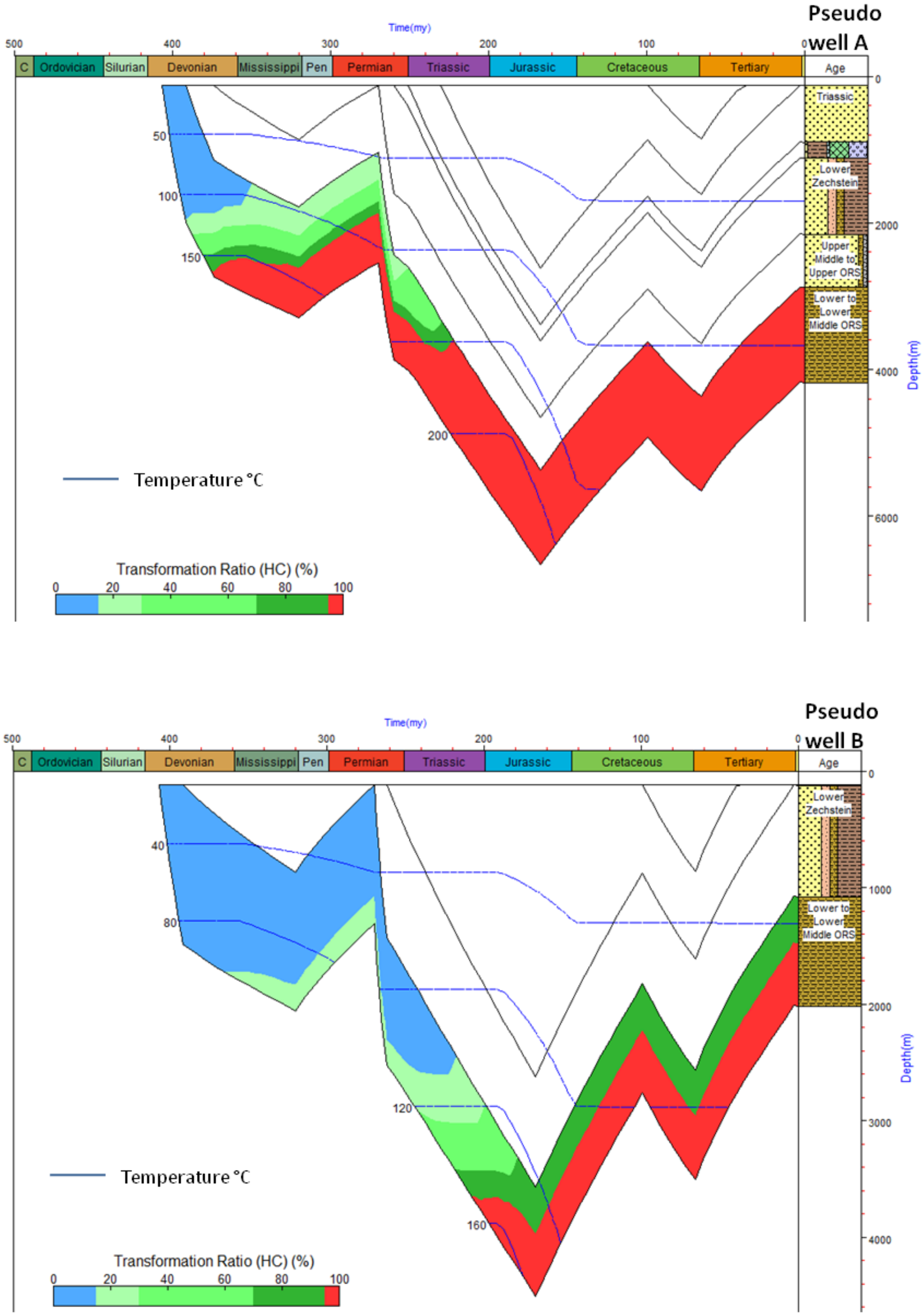


Figure 6-3. Genesis 1D basin model for a mid thermal case in the WOB, using inferred geothermal gradients of 60 °C/km and 40 °C/km for the Devonian and Zechstein to Early Jurassic rift events respectively. The Cretaceous to Cenozoic was kept at a constant value of 25.3 °C/km (based on Holford et al. 2010). Location of pseudo wells A and B is shown in figure 6.1

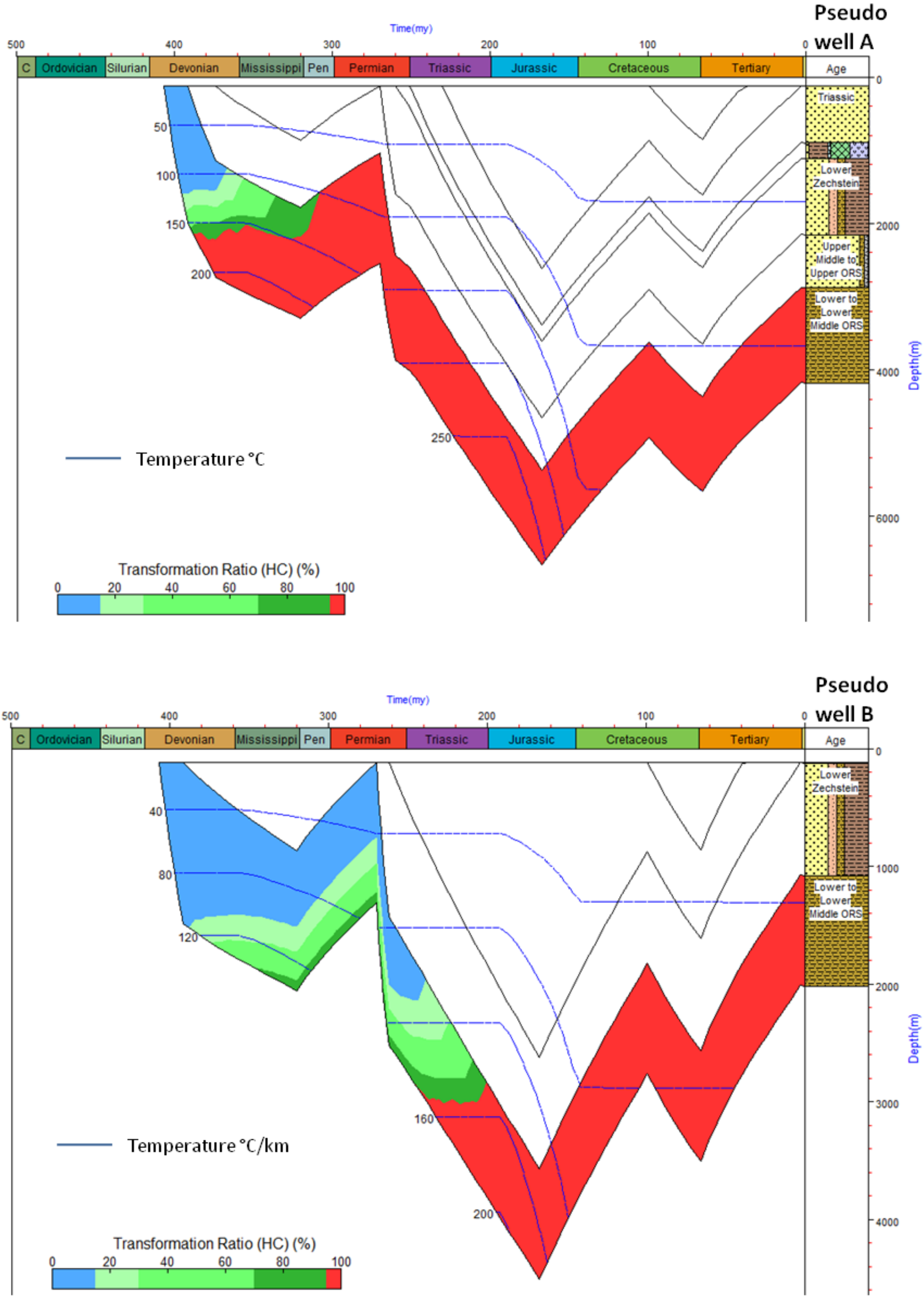


Figure 6-4. Genesis 1D basin model for a high thermal case in the WOB, using inferred geothermal gradients of 75 °C/km and 50 °C/km for the Devonian and Zechstein to Early Jurassic rift events respectively. The Cretaceous to Cenozoic was kept at a constant value of 25.3 °C/km (based on Holford et al. 2010). Location of pseudo wells A and B is shown in figure 6.1

seal, is going to be highly susceptible to this, due to the high percentage of sandstone intervals within the succession (e.g. refer to section 5.2).

Hydrocarbon traps may also be destroyed or reduced in volume during uplift, by either tectonic deformation or surface breaching (Corcoran & Dore 2002). This risk is further exacerbated by seal performance during exhumation. Evaluating the extent of this effect is a significant challenge recognized by the oil industry in recent decades (Nyland et al. 1992; Henriksen et al. 2011).

Play types that rely on mudstone and evaporite seal facies within the Zechstein sequences will be less likely to fracture (refer to section 5.3), because evaporites normally deform plastically over a wide range of depth-pressure-temperature conditions, and hence why they commonly form the most efficient seals in exhumed basins (e.g. East Irish Sea Basin: Seedhouse & Racey (1997); Cowan et al. (1999)). This is well supported by the recognition of long-lived gas accumulations sealed below Lower Cambrian salt in the highly exhumed Lena-Tunguska province of NE Russia (Kontorovitch et al. 1990).

The challenge of petroleum being preserved in basins that have experienced extensive uplift periods is well demonstrated in the West Shetland Basin. Hydrocarbon charging in the West Shetland Basin initiated in the Early Cretaceous, with the majority of hydrocarbons being generated by the end of the Cretaceous. Although it is possible that the Cretaceous charge may account for some of the oil accumulations in the basin (e.g. the Clair Field) (Holmes et al. 1999), it is however thought that the bulk of this charge has been subsequently lost during Cenozoic uplift, and that little or none of it remains in a non-biodegraded state (Jowitt et al. 1999). Much of the remaining non-biodegraded accumulations in the basin (e.g. Victory gas field) are in fact due to

Tertiary hydrocarbon generation (e.g. Goodchild et al. 1999) and possibly remigration.

Similarly, multiple uplift events in the East Irish Sea Basin have dramatically impacted prospectivity. As the case for the WOB, the East Irish Sea Basin is the preserved remnant of a Late Palaeozoic to early Mesozoic rift basin, where subsequent exhumation events has removed the majority of the post-Triassic sedimentary cover, making reconstructions of the burial history highly challenging (Knipe et al. 1993; Duncan et al. 1998). Nonetheless, the East Irish Sea Basin is a prolific hydrocarbon province. Earliest hydrocarbon generation in the basin is believed to have occurred in the Early Jurassic; but this early charge has been subsequently lost due to uplift-associated breaching of seals, before recharging in the Early Tertiary (Stuart & Cowan 1991; Stuart 1993).

In summary, it is conceivable that significant hydrocarbon generation occurred in the WOB during reburial in the Late Permian to Early Jurassic, and before maximum burial was reached in the Early Jurassic. Therefore, seal and trap performance are going to be highly compromised during prolonged uplift events occurring in the Mid-Jurassic to Early Cretaceous and Cenozoic. The difficulty of this is clearly demonstrated in basins like the West Shetland and East Irish Sea Basins, where exploration success relies on Cenozoic recharging. Exploration for a Devonian source-rock play concept in the Orcadian Basin is arguably driven by the success of the Beatrice Field (Inner Moray Firth), where much of this success is probably attributed to Late Cretaceous hydrocarbon generation (e.g. Dore et al. 2002), as opposed to pre-Jurassic hydrocarbon generation in the WOB. It is probable that plays associated with Zechstein evaporite seal facies have the only potential for hydrocarbons to remain intact during exhumation of the WOB. However, in Chapter

5, it was demonstrated that traps that rely on a Zechstein evaporite seal are most likely incapable of being charged sufficiently, due to their position in the basin being outside the interpreted petroleum charge drainage area (refer to section 5.3). Therefore, this research on the WOB has led to the sponsors (Premier Oil) WOB acreage being considered non-prospective and relinquished in its entirety.

Chapter 7

7 Conclusion

The main conclusions drawn from this research study on the tectono-stratigraphic evolution of the West Orkney Basin and its hydrocarbon potential are as follows:

1. Rift structures form complex discordant and concordant relationships with pre-rift Caledonide basement structure. Restoration of basement fabrics to their pre-extensional geometry indicates that the reactivation of basement structures as normal faults has only occurred where the pre-extensional-dip of basement structures is greater than 30°. The relatively high density of relay zones mapped in the WOB, are proposed to be the result of the rift-system forming a partially exploitive relationship with basement fabrics, where extension has been accommodated between segments that have reactivated basement fabrics and segments that have not.
2. Devonian lacustrine source-rocks may be present within the WOB, due to the recognition of a syn-rift sequence overlying basement, which comprises two packages of contrasting seismic facies characteristics that are potentially correlateable to onshore Devonian source-rock and reservoir facies. The syn-rift sequence is truncated at an unconformity; that is probably related to Late Carboniferous inversion of the Great Glen-Walls Boundary Fault system.
3. A second major phase of rifting within the basin, with formation of new faults and reactivation of pre-existing Devonian faults, is interpreted to have initiated in the Late Permian and dwindled into the Early Jurassic. Subsequent extensive exhumation events occurred in the Mid-Jurassic to Early Cretaceous and Cenozoic, with removal of about 2.5 km of Upper Triassic to Lower Jurassic sediments and perhaps 0.5 to 1 km of Upper Cretaceous rocks.
4. The integration of seismic and paleocurrent data has revealed that in the WOB region of the Orcadian Basin, rift topography had a major control on Lower

Middle Devonian depositional drainage patterns; which can be characterised as axial through-going drainage. Source-rock TOC will best be preserved in central areas of the Stack-Skerry sub-basin, away from the main alluvial fan channel systems, such as relay zones. The source-rock GDE model presented for the Lower Middle Devonian, may be applied to others areas of the Orcadian Basin, in order to help evaluate plays based on the presence of a Devonian source-rock.

5. Play concepts having access to a possible Devonian source-rock kitchen are: (1) Lower Devonian aeolian stratigraphic-trap play, (2) Lower Middle Devonian alluvial fan stratigraphic and footwall block play, (3) Upper Middle to Upper Devonian fluvial and aeolian footwall block play, (4) Upper Middle to Upper Devonian fluvial and aeolian sub-unconformity stratigraphic and structural trap play, and (5) Zechstein prograding distal-sand play. However, only two significant leads were recognised in the basin: (1) a structural closure at top-Lower Middle Devonian reservoir interval was mapped, with Hydrocarbons-in-place estimated to be 250 t0 550 mmbo, and (2) a potential region where up-dip stratigraphic pinch-out and closure of the interpreted Upper Middle to Upper Devonian sequence in the basin has been mapped as Lead 2. The major risk associated with these defined play-concepts, and the two leads, are proposed to be presence of an effective seal and trap.
6. Timing of hydrocarbon generation from Devonian source-rocks was modelled using Genesis 1D basin-modelling software from Zetaware, and the results from this indicate that it most probable that the majority of hydrocarbon generation in the basin preceded the end of the second phase of rifting in the basin (Late Permian to Early Jurassic). Therefore, the major risk with play-

concepts based on a Devonian source-rock are considered to be seal integrity during multiple and prolonged uplift events.

8 References

References

Allen, P.A. & Allen, J. R. 2005. Basin Analysis: Principles and Applications, Oxford Blackwell Publishing, 549.

Allan, J.R., Sun, S.Q. & Trice, R. 2006. The deliberate search for stratigraphic and subtle combination traps: where are we now? Geological Society, London, Special Publications, 254, 57-103.

Allen, P.A. & Mange-Rajetzky, M.A. 1992. Devonian-Carboniferous sedimentary evolution of the Clair area, offshore north-western UK: impact of changing provenance. Marine and Petroleum Geology, 9, 29-52.

Anyiam, O.A. & Onuoha, K.M. 2013. A study of hydrocarbon generation and expulsion of the Nkporo Shales in Anambra Basin, Nigeria. Arabian Journal of Geosciences, 1-12.

Astin, T.R. 1990. The Devonian lacustrine sediments of Orkney, Scotland; implications for climate cyclicity, basin structure and maturation history. Journal of the Geological Society, 147, 141-151.

Astin, T.R. 1985. The palaeogeography of the Middle Devonian Lower Eday Sandstone, Orkney. Scottish Journal of Geology, 21, 353-375.

Atkinson, C., Renolds, M. & Hutapea, O. 2006. Stratigraphic traps in the Tertiary rift basins of Indonesia: case studies and future potential. The Deliberate Search for the Stratigraphic Trap, 254, 105. Geological Society Special Publications.

Banks, N.L., Bardwell, K.A. & Musiwa, S. 1995. Karoo rift basins of the Luangwa Valley, Zambia. Geological Society, London, Special Publications, 80(1), 285-295.

Bailey, N.J.L., Burwood, R. & Harriman, G.E. 1990. Application of pyrolysate carbon isotope and biomarker technology to organofacies definition and oil correlation problems in North Sea basins. Organic Geochemistry,16, 1157–1172.

Barr, D., Holdsworth, R.E. & Roberts, A.M. 1986. Caledonian ductile thrusting in a Precambrian metamorphic complex: the Moine of north-western Scotland. Geological Society of America Bulletin, 97, 754–764.

Blackbourn, G.A. 1981a. Probable Old Red Sandstone conglomerates around Tongue and adjacent areas, north Sutherland. Scottish Journal of Geology, 17, 103–118.

Blackbourn, G.A. 1981b. Correlation of Old Red Sandstones (Devonian) outliers in the Northern Highlands of Scotland. Geological Magazine, 118, 409–414.

Blair, T.C. & McPherson, J.G. 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Journal of sedimentary research, 64.

Blystad, P., Brekke, H., Faerseth, R.B., Larsen, B.T., Skogseid, J. & Toudbakken, B. 1995. Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea region. Norwegian Petroleum Directorate Bulletin, 8.

Booth, J., Swiecicki, T. & Wilcockson, P. 1993. The tectono-stratigraphy of the Solan Basin, west of Shetland. In: Parker, J. R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. The Geological Society, London, 987-998.

Bracken, B.R. 1994. SEPM Core Workshop in Lacustrine Reservoirs and Depositional Systems, Syn-rift lacustrine beach and deltaic sandstone reservoirs

— pre-salt (Lower Cretaceous) of Cabinda, Angola, west Africa, eds Lomando A.J., Schreiber B. C., Harris P.M. 19, pp 173–200.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea continental margin, with emphasis on the Vøring and Møre basins. In: NØTTVEDT, A. (eds) Dynamics of the Norwegian Margin. Geological Society, London, Special Publications, 167, 327-378.

Brewer, J.A. & Smythe, D.K. 1984. MOIST and the continuity of crustal reflector geometry along the Caledonian – Appalachian orogeny. Journal of the Geological Society, London, 141, 105–120.

Bruce, D.R.S. & Stemmerik, L. 2003: The Carboniferous of the Northern North Sea. In Evans. D., Graham, C., Armour, A. & Barhurst, P. (eds) The Millennium Atlas: petroleum geology of the Central and Northern North Sea. London: The Geological Society of London, 83–89.

Butler, R.W.H. 1986. Structural evolution in the Moine of northwest Scotland: a Caledonian linked thrust system?. Geological Magazine / Volume 123 / Issue 01 / January 1986, 1-11.

Butler, R.W.H. 2010. The role of thrust tectonic models in understanding structural evolution in NW Scotland Geological Society, London, Special Publications, 2010, 335, 293-320.

Butler, R.W.H. & Coward, M.P. 1984. Geological constraints, structural evolution and deep geology of the northwest Scottish Highlands. Tectonics, 3, 347–365.

Butler, R.W.H. Holdsworth, R.E. Lloyd, G.E. 1997. The role of basement reactivation during continental deformation. Journal of the Geological Society, London, 154, 69-71.

Cavanagh, A., diPrimio, R. & Horsfield, B., 2005. Thermal history, ice loading and inversion of the SW Barents sea revealed by basin modelling., Geophysical Research Abstracts. European Geosciences Union, EGU Vienna.

Cartwright, J., Huuse, M., & Aplin, A. 2007. Seal bypass systems. AAPG bulletin, 91, 1141-1166.

Catuneanu, O. 2006. Principles of sequence stratigraphy. Elsevier.

Changsong, L., Qi, Y., & Sitian, L. 1991. Structural and depositional patterns of the Tertiary Baise Basin, Guang Xi Autonomous Region (southeastern China): a predictive model for fossil fuel exploration. Lacustrine facies analysis, 75-92.

Cohen, A.S. 1990. A Tectonostratigraphic Model for Sedimentation in Lake Tanganyika , Africa. In Katz, B. Lacustrine Basin Exploration — Case Studies and Modern Analogs, AAPG Mem. 50: 137-150

Collier, R. E. L., & Gawthorpe, R. L. 1995. Neotectonics, drainage and sedimentation in central Greece: insights into coastal reservoir geometries in syn-rift sequences. Geological Society, London, Special Publications, 80, 165-181.

Corcoran, D.V., & Doré, A.G. 2002. Top seal assessment in exhumed basin settings—Some insights from Atlantic margin and borderland basins. Norwegian Petroleum Society Special Publications, 11, 89-107.

Cowan, G., Burley, D., Hoey, N., Holloway, P., Birmingham, P., Beveridge, N., & Sylta, Ø. 2004. Oil and gas migration in the Sherwood Sandstone of the East Irish Sea Basin. In Petroleum geology of Northwest Europe: Proceedings of the 5th Conference, 1383-1398.

Coward, M.P. 1988. The Moine Thrust and the Scottish Caledonides. In: Mitra, G., Wojtal, S. (eds) Geometries and mechanics of thrusting, with special reference to the Appalachians. Geological Society of America, Special Paper, 222 1 – 16.

Coward, M.P., Dewey, J.F., Hempton, M., Holroyd, J. 2003. Tectonic evolution. 17-33 in the Millenium Atlas: petroleum geology of the central and northern North Sea. Evans, D, Graham, C, Armour, A, and Bathurst, P (editors and co-ordinators). The Geological Society of London.

Coward, M.P & Enfield, M.A. 1987. The structure of the West Orkneys and associated basins. In: Brooks et al. (eds) Proceedings of the 3rd Conference on the Petroleum Geology of NW Europe.

Coward, M.P., Enfield, M.A. & Fischer, M.W. 1989. Devonian basins of Northern Scotland: extension and inversion related to Late Caledonian – Variscan tectonics. In: Cooper, M. A. & Williams, G. D. (eds) Inversion Tectonics. Geological Society, London, Special Publications, 44, 275–308.

Crampton, C.B. & Curruthers, R.G. 1914. The geology of Caithness. Memoir of the Geological Survey of Great Britain, Sheets 110 and 116, with parts of 109, 115 and 117 (Scotland). HMSO, Edinburgh.

Dean, K., Mclachlan, K. & Chambers, A. 1999. Rifting and the development of the Faroe-Shetland Basin. In Geological Society, London, Petroleum Geology Conference series, 5, 533-544.

Dixon, R.J., Moore, J.K.S., Bourne, M., Dunn, E., Haig, D.B., Hossack, J. & Simmons, C.J. 2010. Integrated petroleum systems and play fairway analysis in a complex Palaeozoic basin: Ghadames-Illizi Basin, North Africa. In Geological Society, London, Petroleum Geology Conference series, 7, 735-760).

Donovan, R.N. 1975. Devonian lacustrine limestones at the margin of the Orcadian Basin, Scotland. Journal of the Geological Society, London, 131, 489–510.

Donovan, A.D. 2003. Depositional topography and sequence development. In Shelf Margin Deltas and Linked Downslope Petroleum Systems, Gulf Coast Section, SEPM Foundation, 23rd Annual Research Conference, 493-522.

Duncan, W.I., Green, P.F., & Duddy, I.R. 1998. Source rock burial history and seal effectiveness: key facets to understanding hydrocarbon exploration potential in the East and Central Irish Sea Basins. AAPG bulletin, 82(7), 1401-1415.

Doré, A.G. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. Palaeogeography Palaeoclimatology Palaeoecology, 87, 441-492.

Doré, A.G., Corcoran, D.V. & Scotchman, I. C. 2002. Prediction of the hydrocarbon system in exhumed basins, and application to the NW European margin. Geological Society, London, Special Publications, 196, 401-430.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., & Fichler, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. In Geological Society, London, Petroleum Geology Conference series, 5, 41-61.

Durand, B. & Monin, J. C. 1980. Elemental analysis of kerogens (C, H, O, N, S, Fe). Kerogen: Paris, Editions Technip, 113-142.

Earle M.M., Jankowski, E. J. & Vann, I.R. 1989. Structural and stratigraphic evolution of the Faeroe-Shetland channel and northern Rockall trough. in Extensional tectonics and stratigraphy of the North Atlantic margins, eds Tankard A. J., Balkwill H. R. 46:461–469, American Association of Petroleum Geologists Memoirs.

Einsele, G. 2000. Sedimentary basins: evolution, facies, and sediment budget. Springer.

Emery, D. & Myers, K.J. 1996. Sequence Stratigraphy. Blackwell, Oxford, UK, 297.

Evans, D.J. 1997. Estimates of the eroded overburden and the Permian–Quaternay subsidence history of the area west of Orkney. Scottish Journal of Geology, 33, 169-181.

Eliet, P.P. & Gawthorpe, R.L. 1995. Drainage development and sediment supply within rifts, examples from the Sperchios basin, central Greece. Journal of the Geological Society, 152, 883-893.

Elliott, D. & Johnson, M.R.W. 1980. Structural evolution in the northern part of the Moine thrust belt, NW Scotland. Transactions of the Royal Society of Edinburgh, 71, 69-96.

Enfield, M.A. & Coward, M.P. 1987. The structure of the West Orkney Basin, northern Scotland. Journal of the Geological Society, London, 144, 871–884.

Eschard, R., Lemouzy, P., Bacchiana, C., Desaubliaux, G., Parpant, J., & Smart, B. 1998. Combining sequence stratigraphy, geostatistical simulations, and production data for modeling a fluvial reservoir in the Chaunoy field (Triassic, France). AAPG bulletin, 82(4), 545-568.

Fettes, D.J., Long, C.B., Max, M.D. & Yardley, B.W.D. 1985. Grade and time of metamorphism in the Caledonide Orogen of Britain and Ireland. In: Harris, A.L. (ed.) The Nature and Timing of Orogenic Activity in the Caledonian Rocks of the British Isles. Geological Society of London, Memoirs, 9, 41–53.

Fossen, H. 1992. The role of extensional tectonics in the Caledonides of South Norway. Journal of Structural Geology, 14, 1033–1046.

Fossen. H. 2010. Extensional tectonics in the North Atlantic Caledonides: a regional view Geological Society, London, Special Publications 2010; 335; 767-793.

Fraser, A. J. 2010. A regional overview of the exploration potential of the Middle East: a case study in the application of play fairway risk mapping techniques. In Geological Society, London, Petroleum Geology Conference series. 7, 791-800.

Fraser, A.J. & Gawthorpe, R.L. 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. Geological Society, London, Special Publications, 55, 49-86.

Freeman, B., Yielding, G., Needham, D. T. & Badley, M.E. 1998. Fault seal prediction: the gouge ratio method. Geological Society, London, Special Publications, 127, 19-25.

Frostick, L. & Reid, I. 1989. Is structure the main control of river drainage and sedimentation in rifts?. Journal of African Earth Sciences (and the Middle East), 8, 165-182.

Frostick, L. E. & Reid, I. 1990. Structural control of sedimentation patterns and implication for the economic potential of the East African Rift basins. Journal of African Earth Sciences (and the Middle East), 10, 307-318.

Gardiner, A. R. 2006. The variability of turbidite sandbody pinchout and its impact on hydrocarbon recovery in stratigraphically trapped fields. Geological Society, London, Special Publications, 254, 1, 267-287

Gawthorpe, R.L. & Hurst, J.M. 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. Journal of the Geological Society, 150, 1137-1152.

Gawthorpe, R.L. & Leeder, M.R. 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research, 12, 195-218.

Geikie, A. 1878. On the Old Red Sandstone of Western Europe. Transactions of the Royal Society of Edinburgh, 28, 345–452.

Glennie, K.W, Higham, J. & Stemmerik, L. 2003, 'The Permian of the Northern North Sea'. in D Evans, C Graham, A Armour & P Barhurst (eds), The Millennium Atlas: petroleum geology of the Central and Northern North Sea. Geological Society of London, 91-103.

Gluyas, J. & Swarbrick, R. 2004. Petroleum geoscience. John Wiley & Sons.

Goodchild, M.W., Henry, K.L., Hinkley, R.J. & Imbus, S.W. 1999. The Victory gas field, West of Shetland. In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society, London, 713–724.

Green, P.F., Duddy, I.R., & Bray, R.J. 1995. Applications of thermal history reconstruction in inverted basins. Geological Society, London, Special Publications, 88, 149-165.

Hamilton R.F.M., Trewin N.H. 1988. in Devonian of the World, Environmental controls on fish faunas of the Middle Devonian Orcadian Basin, eds McMillan N.J., Embry A.F., Glass D.J. (Canadian Society of Petroleum Geologists Memoirs), 14, 589–600.

Hantschel, T. & Kauerauf, A. I. 2009. Fundamentals of basin and petroleum systems modelling. Berlin: Springer, 31-86

Hart, B.S., Sibley, D.M., Flemings, P.B., 1997. Seismic stratigraphy, facies architecture, and reservoir character of a Pleistocene shelf-margin delta complex, Eugene Island Block 330 Field, offshore Louisiana. AAPG Bull. 81, 380– 397.

Henriksen, E., Bjørnseth, H.M., Hals, T.K., Heide, T., Kiryukhina, T., Kløvjan, O.S. & Stoupakova, A. 2011. Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems. Geological Society, London, Memoirs, 35, 271-281.

Herries, R., Poddubiuk, R., & Wilcockson, P. 1999. Solan, Strathmore and the back basin play, West of Shetland. In Geological Society, London, Petroleum Geology Conference series 5, 693-712.

Hillier, S. & Marshall, J.E. A. 1992. Organic maturation, thermal history and hydrocarbon generation in the Orcadian Basin, Scotland. Journal of the Geological Society, 149, 491-502.

Hoshino. K., Koide, H., Inami, K., Iwamura, S & Mltsi, S. 1972. Mechanical properties of Japanese Tertiary sedimentary rocks under high confining pressures. Geological Survey of Japan.

Hitchen, K., Stoker, M.S., Evans, D. & Beddoe-Stephens, B. 1995. Permo-Triassic sedimentary and volcanic rocks in basins to the north and west of Scotland. In: Boldy, S.A.R. (ed.) Permian and Triassic rifting in Northwest Europe. Geological Society, London, Special Publications, 91, 87–102.

Holford, S.P., Green, P.F., Duddy, I.R., Turner, J.P., Hillis, R.R. & Stoker, M.S. 2009. Regional intraplate exhumation episodes related to plate-boundary deformation. Geological Society of America Bulletin, 121, 1611-1628.

Holdford, S. P., Green, P. F., Hillis, R. R., Underhill, J. R., Stoker, M. S., Duddy, I. R., 2010., I Multiple post-Caledonian exhumation episodes across NW Scotland revealed by apatite fission-track analysis. Journal of the Geological Society, 167, 675-694.

Holdsworth, R. E., Strachan, R. A. & Alsop, G. I. 2001. Solid Geology of the Tongue District. Memoir of the British Geological Survey, Sheet 114E (Scotland). HMSO, London.

Holmes, A.J., Griffith, C.E. & Scotchman, I.C. 1999. The Jurassic Petroleum System of the West of Britain Atlantic Margin – an integration of tectonics, geochemistry and basin modelling. In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of

Northwest Europe: Proceedings of the 5th Conference.Geological Society, London, 1351–1365.

Illies, J.H. 1972. The Rhine graben rift system-plate tectonics and transform faulting. Geophysical Surveys, 1, 1, 27-60

Johnstone, G.S. & Mykura, W. 1989. British Regional Geology: The Northern Highlands of Scotland (4th edition). HMSO, London.

Jones, S.M., White, N., Clarke, B.J., Rowley, E. & Gallagher, K. 2002. Present and past influence of the Iceland Plume on sedimentation. Geological Society, London, Special Publications, 196, 13-25.

Jowitt, R., Hindle, A., Jones, D. & Rose, P. 1999. Petroleum systems analysis of the Paleocene Play in the West of Shetlands Area. In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society, London, 1367–1382.

Karp, T., Scholz, C.A. & McGlue, M.M. 2012. Structure and stratigraphy of the Lake Albert rift, East Africa: observations from seismic reflection and gravity data. AAPG Special Publication.

Katz, B.J. 2001. Lacustrine basin hydrocarbon exploration–current thoughts. Journal of paleolimnology, 26, 161-179.

Katz, B.J. & Xingcai, L. 1998. Summary of the AAPG research symposium on lacustrine basin exploration in China and Southeast Asia. AAPG Bulletin, 82, 1300-1307.

Kearey, P., Brooks, M. & Hill, I. 2002. An introduction to geophysical exploration. John Wiley & Sons.

Kelly, S.B. 1992. Milankovitch cyclicity recorded from Devonian non-marine sediments. Terra Nova, 4, 578-584.

Kettel, D. 1997. The dynamics of gas flow through rock salt in the scope of time. Norwegian Petroleum Society Special Publications, 7, 175-185.

Knipe, R.J., Cowan, G. & Balendran, V.S. 1993. The tectonic history of the East Irish Sea Basin with reference to the Morecambe Fields. In Geological Society, London, Petroleum Geology Conference series, 4, 857-866.

Kontorovich, A.E., Mandel'Baum, M.M., Surkov, V.S., Trofimuk, A.A. & Zolotov, A.N. 1990. Lena-Tunguska Upper Proterozoic-Palaeozoic petroleum superprovince. Geological Society, London, Special Publications, 50, 473-489.

Krooss, B.M., Leythaeuser, D. & Schaefer, R.G. 1992. The Quantification of Diffusive Hydrocarbon Losses Through Cap Rocks of Natural Gas Reservoirs--A Revaluation: Geologic Note. AAPG Bulletin, 76, 403-406.

Lambiase, J.J. & Bosworth, W. 1995. Structural controls on sedimentation in continental rifts. Geological Society, London, Special Publications, 80, 117-144.

Lapworth, C. 1885. The Highland controversy in British Geology; its causes, course and consequence. Nature, 32, 558-559

Larsen, M., Rasmussen, T. & Hjelm, L. 2010. Cretaceous revisited: exploring the syn-rift play of the Faroe–Shetland Basin. In Geological Society, London, Petroleum Geology Conference series, 7, 953-962.

Leeder, M.R. & Gawthorpe, R.L. 1987. Sedimentary models for extensional tilt-block/half-graben basins. Geological Society, London, Special Publications, 28, 139-152.

Leslie, A.G. Krabbendam, M. Kimbell, G.S. & Strachan, R.A. 2010. Regional-scale lateral variation and linkage in ductile thrust architecture: the Oykel Transverse Zone, and mullions, in the Moine Nappe, NW Scotland Geological Society, London, Special Publications, 335, 359-381.

Macgregor, D.S. 1995. Hydrocarbon habitat and classification of inverted rift basins. Geological Society, London, Special Publications, 88, 83-93.

Magnavita, L.P. & da Silva, H.T. 1995. Rift border system: the interplay between tectonics and sedimentation in the Recôncavo basin, northeastern Brazil. AAPG bulletin, 79, 1590-1607.

Magoon, L.B. & Dow, W.G. 1994. The petroleum system. The petroleum system—From source to trap: AAPG Memoir, 60, 3-24.

Makhous, M. & Galushkin, Y.I. 2005. Basin analysis and modeling of the burial, thermal and maturation histories in sedimentary basins. Paris, France: Editions Technip.

Makowitz, A., Lander, R.H., & Milliken, K.L. 2006. Diagenetic modeling to assess the relative timing of quartz cementation and brittle grain processes during compaction. AAPG bulletin, 90, 873-885.

Mark, D.F., Green, P.F., Parnell, J., Kelley, S.P., Lee, M.R., Sherlock, S.C. 2008. Late Paleozoic hydrocarbon migration through the Clair field, West of Shetland, UK Atlantic margin Geochimica et Cosmochimica Acta, 72, 2510-2533.

Marshall, J.E. A. 1998. The recognition of multiple hydrocarbon generation episodes: an example from Devonian lacustrine sedimentary rocks in the Inner Moray Firth, Scotland. Journal of the Geological Society, 155, 335-352.

Marshall, J.E.A., Astin, T.R., Brown, J.F., Mark-Kurik, E. & Lazauskiene, J. 2007. Recognising the Kacak Event in the Devonian terrestrial environment and its implications for understanding land-sea interactions. In, Becker, R.T. and Kirchgasser, W.T. (eds.) Devonian Events and Correlations. London, UK, Geological Society of London, 133-155.

Marshall, J.E.A., Brown, J.F. & Hindmarsh, S. 1985. Hydrocarbon source rock potential of the Devonian rocks of the Orcadian Basin. Scottish Journal of Geology, 21, 301-320.

Marshall, J.E.A. & Hewett, A.J. 2003. Devonian. In, Evans, D., Graham, C., Armour, A. and Bathurst, P. (eds.) The Millennium Atlas: petroleum geology of the central and northern North Sea. London, Geological Society of London, 65-81.

Marshall, J.E.A., Rogers, D.A. & Whiteley, M. J. 1996. Devonian marine incursions into the Orcadian Basin, Scotland. Journal of the Geological Society, 153, 451-466.

Mayall, M.J., Yeilding, C.A., Oldroyd, J.D., Pulham, A.J., Sakurai, S., 1992. Facies in a shelf-edge delta—an example from the subsurface of the Gulf of Mexico, middle Pliocene, Mississippi Canyon, Block 109. AAPG Bull. 76, 435– 448.

McCalpin, J. 1983. Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado. Colorado School of Mines Press.

McClay, K.R., Norton, M. G., Coney, P. & Davis, G. H. 1986. Collapse of the Caledonian orogen and the Old Red Sandstone. Nature, 323, 147–149.

McConnell, R.B. 1972. Geological Development of the Rift System of Eastern Africa Geological Society of America Bulletin, 83, 2549-2572

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth and planetary science letters, 40, 25-32.

McGee, D.T., Bilinski, P. W., Gary, P. S., Pfeifer, D. S. & Scheiman, J. L. 1993. Geologic models and reservoir geometries of Auger Field, Deepwater Gulf of Mexico. In: Weimer, P., Bouma, A.H., Perkins, R.F. (Eds.), Submarine Fans and Turbidite Systems, Gulf Coast Section of SEPM 15th Annual Research

Mendum, J.R., Barber, A.J., Butler, R.W.H., Flinn, D.,Goodenough, K.M., Krabbendam, M., Park, R.G. & Stewart, A.D. 2008. Lewisian, Torridonian and Moine Rocks of Scotland, Geological Conservation Review Series, No. 34, Joint Nature Conservation Committee, Peterborough, 598 pages, illustrations, A4 hardback, ISBN 978 1 86107 566 6

Morley, C.K., Nelson, R.A., Paton, T.L., Munn, S.G. 1990. Transfer Zones in the East African Rift System and Their Relevance to Hydrocarbon Exploration in Rifts. AAPG Bulletin. 74, 8, 1234-1253

Morton, N. 1989. Jurassic sequence stratigraphy in the Hebrides Basin, NW Scotland. Marine and petroleum geology, 6, 243-260.

Moy, D.J. & Imber, J. 2009. A critical analysis of the structure and tectonic significance of rift-oblique lineaments ('transfer zones') in the Mesozoic-Cenozoic succession of the Faroe-Shetland Basin, NE Atlantic margin. Journal of the Geological Society 166, 831-844.

Mykura, W. 1976. British regional geology: Orkney and Shetland. HMSO, Edinburgh

Newman, M.S.J., Reeder, M.L., Woodruff, A.H.W. & Hatton, I.R. 1993. The geology of the Gryphon oil field. In Geological Society, London, Petroleum Geology Conference series, 4, 123-133.

Norton, M. 1986. Late Caledonian extension in western Norway: a response to extreme crustal thickening. Tectonics, 5, 192–204.

Nyland, B., Jensen, L.N., Skagen, J.L., Skarpnes, O. & Vorren, T. 1992. Tertiary uplift and erosion in the Barents Sea: magnitude, timing and consequences. Structural and tectonic modelling and its application to petroleum geology, 153-162.

Ohm, S.E., Karlsen, D.A. & Austin, T.J.F. 2008. Geochemically driven exploration models in uplifted areas: Examples from the Norwegian Barents Sea. AAPG bulletin, 92, 1191-1223.

Olsen, P.E. 1986. A 40-million-year lake record of early Mesozoic orbital climatic forcing. Science, 234(4778), 842-848.

O'reilly, K.J. 1983. Composition and age of the conglomerate outliers around the Kyle of Tongue, north Sutherland, Scotland. Proceedings of the Geologists' Association, 94, 53–64.

Owen M.A. 1994. The controls on reservoir properties of Devonian sandstones in the Orcadian Basin, North East Scotland. PhD thesis, Univ. Reading, UK.

Peach, B.N., Horne, J., Gunn, W., Clough, C.T., Hinxman, L.W. & Teall, J.J.H. 1907. The Geological Structures of the NW Highlands of Scotland. Memoirs of the Geological Survey of Great Britain. HMSO, Glasgow.

Poelchau, H.S., Baker, D.R., Hantschel, T., Horsfield, B. & Wygrala, B. 1997. Basin simulation and the design of the conceptual basin model. In Petroleum and basin evolution, 3-70. Springer Berlin Heidelberg.

Pollack, H.N., Hurter, S.J., & Johnson, J. R. 1993. Heat flow from the Earth's interior: analysis of the global data set. Reviews of Geophysics, 31, 267-280.

Porębski, S.J., & Steel, R. J. 2003. Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands. Earth-Science Reviews, 62, 283-326.

Powell, D. & Glendinning, N.R.W. 1990. Late Caledonian extensional reactivation of a ductile thrust in NW Scotland. Journal of the Geological Society, London, 147, 979-987.

Prosser, S. 1993. Rift-related linked depositional systems and their seismic expression. Geological Society, London, Special Publications, 71, 35-66.

Rayner, D.H. 1963. The Achanarras Limestone of the Middle Old Red Sandstone, Caithness, Scotland. In Proceedings of the Yorkshire Geological and Polytechnic Society, Geological Society of London, 34, 2, 117-138.

Richards, P., Duncan, I., Phipps, C., Pickering, G., Grzywacz, J., Hoult, R., & Merritt, J. 2006. Exploring for fan and delta sandstones in the offshore Falklands Basins. Journal of Petroleum Geology, 29(3), 199-214.

Ritchie, J.D., Ziska, H., Johnson, H. & Evans, D. 2011. Geology of the Faroe-Shetland Basin and adjacent areas. British Geological Survey.

Robert, P. 1985. Histoire geothermique et diagenese organique [Geothermal history and organic diagenesis]. Bull. Centres Rech. Expl. Prod. Elf-Aquitaine, Mem.

Roberts, A.M, Holdsworth, R.E. 1999. Linking onshore and offshore structures: Mesozoic extension in the Scottish Highlands. Journal of the Geological Society, 156, 1062-1064.

Rogers, D.A. & Astin, T.R. 1991. Ephemeral lakes, mud pellet dunes and wind-blown sand and silt: reinterpretations of Devonian lacustrine cycles in north Scotland. Lacustrine Facies Analysis: Special Publication 13 of the IAS, 30, 199.

Rogers, D.A., Marshall, J.E.A. & Astin, T.R. 1989. Short Paper: Devonian and later movements on the Great Glen fault system, Scotland. Journal of the Geological Society, 146, 369-372.

Salvador, A. & Leon, H.J. 1992. Quiriquire Field –Venezuela. Eastern Venezuela (Maturin) Basin. In Beaumont, E.A. & Foster, N.H. (eds.) Stratigraphic Traps III.

Seedhouse, J.K., & Racey, A. 1997. Sealing capacity of the Mercia Mudstone Group in the East Irish Sea Basin: implications for petroleum exploration. Journal of Petroleum Geology, 20(3), 261-286.

Seranne, M. 1992. Devonian extensional tectonics versus Carboniferous inversion in the northern Orcadian basin. Journal of the Geological Society, London, 149, 27–37.

Shepherd, M. 2009. Oil field production geology. American Association of Petroleum Geologists.

Silalahi, H.S. M.P., Pyles, D., Bouroullec, R., Anderson, D., Clark, J. & Sonnenberg, S. A. 2009. Stratigraphic Architecture of Slope Deposits Associated with Prograding Margins, Sobrarbe Formation: Ainsa Basin, Spain (Doctoral dissertation, Colorado School of Mines).

Snyder, D.B. 1990. The Moine Thrusts in the BIRPS data set. Journal of the Geological Society, London, 147, 81–86.

Snyder, D. & Hobbs, R. W. 2000. The BIRPS Atlas 2: A Second Decade of Deep Seismic Profiling. Geological Society, London.

Soper, N.J. & Berber, AJ. 1982. A model for the deep structure of the Moine Thrust Zone. Journal of the Geological Society, London, 127-238.

Speed, R.G. 1999. Kerogen variation in a Devonian half graben system (Doctoral dissertation, University of Southampton).

Stoker, M.S., Hithcen, K. & Graham, C.C. 1993. The Geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas. United Kingdom Offshore Regional Report. HMSO, London.

Stoker, M.S., Holford, S.P., Hillis, R.R., Green, P.F. & Duddy, I.R. 2010. Cenozoic post-rift sedimentation off northwest Britain: Recording the detritus of episodic uplift on a passive continental margin. Geology, 38(7), 595-598.

Streule, M.J., Strachan, R. A., Searle, M.P. & Law, R.D. 2010. Comparing Tibet-Himalayan and Caledonian crustal architecture, evolution and mountain building processes. From: Law, R. D., Buter, R.W. H., Holdsworth, R. E., Krabbendam, M. & Strachan, R. A. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. Geological Society, London, Special Publications, 335, 207–232.

Stuart, I.A. 1993. The geology of the North Morecambe Gas Field, East Irish Sea Basin. In Geological Society, London, Petroleum Geology Conference series (4, 883-895). Geological Society of London.

Stuart, I.A. & Cowan, G. 1991. The South Morecambe Field, Blocks 110/2a, 110/3a, 110/8a, UK East Irish Sea. Geological Society, London, Memoirs, 14(1), 527-541.

Surlyk, F. 1991. Sequence stratigraphy of the Jurassic lowermost Cretaceous of east Greenland. AAPG Bulletin, 75, 1468-1488.

Tate, M.P. 1993. Structural framework and tectono-stratigraphic evolution of the Porcupine Seabight Basin offshore western Ireland. Marine and Petroleum Geology, 10, 95-123.

Tegelaar, E.W. & Noble, R.A. 1994. Kinetics of hydrocarbon generation as a function of the molecular structure of kerogen as revealed by pyrolysis-gas chromatography. Organic Geochemistry, 22(3), 543-574.

Telford, W.M. & Sheriff, R.E. 1990. Applied geophysics (Vol. 1). Cambridge university press.

Tiercelin, J.J. 1991. Natural resources in the lacustrine facies of the Cenozoic rift basins of East Africa. Lacustrine Facies Analysis: Special Publication 13 of the IAS, 30, 3.

Tiercelin, J.J. 1990. Rift-basin sedimentation: responses to climate, tectonism and volcanism. Examples of the East African Rift. Journal of African Earth Sciences (and the Middle East), 10(1), 283-305.

Torsvik, T.H. & Andersen, T.B. 2002. The Taimyr Fold Belt, Arctic Siberia: Timing of pre-fold remagnetisation and Regional tectonics. Tectonophysics, 352, 335-348.

Trewin N.H. 1986. Palaeoecology and sedimentology of the Achanarras fish bed of the Middle Old Red Sandstone, Scotland. Transactions of the Royal Society of Edinburgh, Earth Sciences 77:21–46.

Trewin, N. H. 2002. The geology of Scotland. Geological Society of London.

Trudgill, B.D. 2002. Structural controls on drainage development in the Canyonlands grabens of southeast Utah. AAPG bulletin, 86(6), 1095-1112.

Underdown, R. & Redfern, J. 2007. The importance of constraining regional exhumation in basin modelling: a hydrocarbon maturation history of the Ghadames Basin, North Africa. Petroleum Geoscience, 13(3), 253-270.

Underhill, J.R. 1991. Controls on Late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: a critical test of a key segment of Exxon's original global cycle chart. Basin Research, 3(2), 79-98.

Underhill, J.T. & Partington, M.A. 1993. Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. In Geological Society, London, Petroleum Geology Conference series (Vol. 4, pp. 337-345). Geological Society of London.

Ungerer, P., Burrus, B., Doligez, P.Y., Chenet, & Bessis, F. 1990. Basin Evaluation by Integrated Two Dimensional Modelling of Heat Transfer, Fluid Flow, Hydrocarbon Generation, and Migration : AAPG Bulletin, 74, 309.

Verstralen, I., Hartley, A. & Hurst, A. 1995. The sedimentological record of a late Jurassic transgression: Rona Member (Kimmeridge Clay Formation equivalent), West Shetland Basin, UKCS. Geological Society, London, Special Publications, 94(1), 155-176.

Watson, J. 1985. Northern Scotland as an Atlantic-North Sea divide. J. gcol. Soc. London, 142, 221-243.

Welte, D.H. & Yalcin, M.N. 1988. Basin modelling—a new comprehensive method in petroleum geology. Organic Geochemistry, 13(1), 141-151.

Welte, D.H. & Yukler, M.A. 1981. Petroleum origin and accumulation in basin evolution--a quantitative model. AAPG Bulletin, 65(8), 1387-1396.

White, N. & Lovell, B. 1997. Measuring the pulse of a plume with the sedimentary record. Nature, 387(6636), 888-891.

Wilson, R.W. Holdsworth, R.E. Wild, L.E. Mccaffrey, K.J.W. England, R.W. Imber J. Strachan. R.A. 2010. Basement-influenced rifting and basin development: a reappraisal of post-Caledonian faulting patterns from the North Coast Transfer Zone, Scotland. From: Law, R.D., Buter, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. Geological Society, London, Special Publications, 335, 207–232.

Winchester, J.A. 1974. The zonal pattern of regional metamorphism in the Scottish Caledonides. Journal of the Geological Society, 130, 509–524.

Ziegler, P. A. (1990). Geological atlas of western and central Europe. (The Hague: Shell Internationale Maastchappij, BV.)

9 APPENDIX 1

9.1 Overview of the basin modelling principles used in Chapter 6

Basin modelling was conducted in Chapter 6 of the thesis in order to assess timing of hydrocarbon generation in the basin. This study used: Genesis 1D basin modelling software from Zetaware.

9.1.1 Constructing a burial history plot:

To model burial history of a pseudo well in the basin, Genesis requires the following input parameters for each stratigraphic event: (1) age deposition begins and stops, (2) sequence thickness, and (3) lithology.

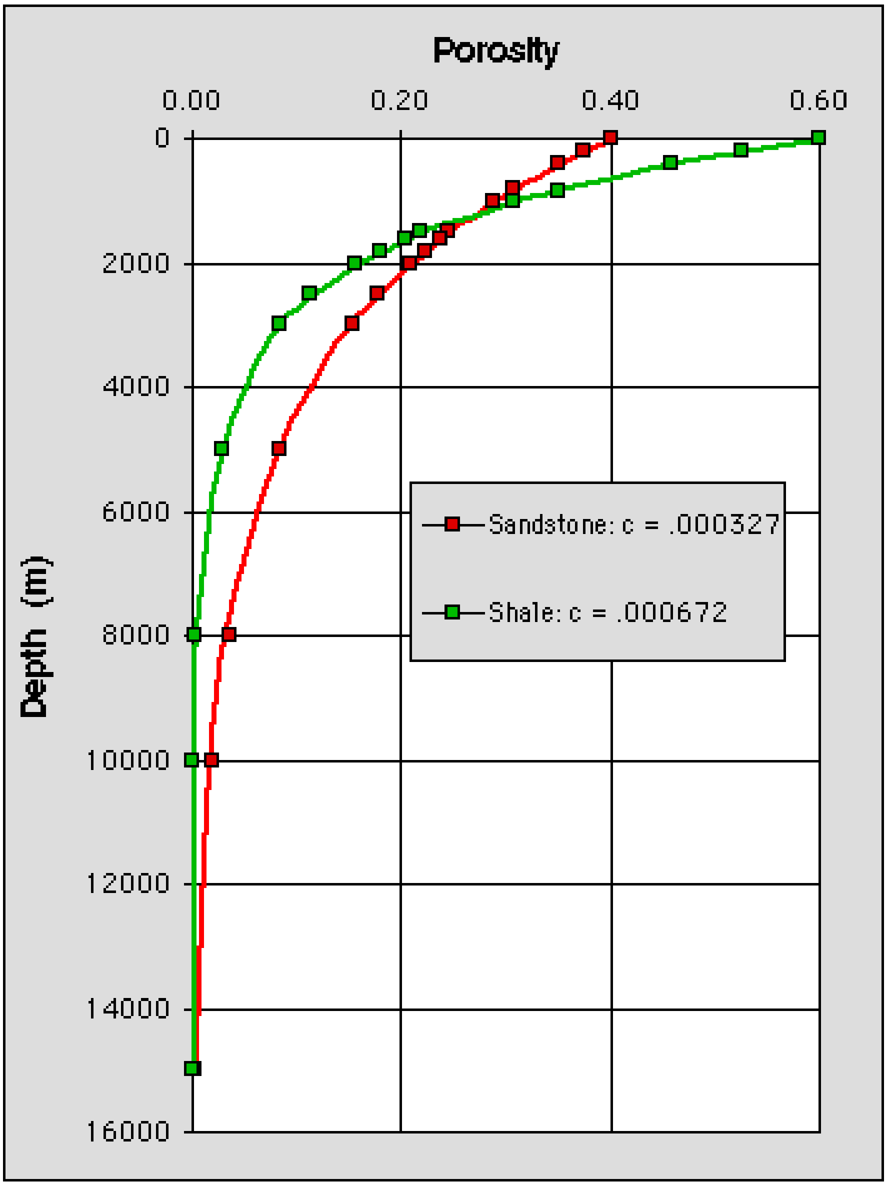
Additionally, unconformities and deposition events can be entered into Genesis in such an order that a) at any time, the net deposited thickness is greater or equal to zero up to that point in time; and b) the net thickness is zero at the end of the last event (Makowitz et al. 2006; Underdown & Redfern 2007; Anyiam & Onuoha 2013).

The deposition rate is calculated from the depth and ages, as well as the lithologies involved. The compaction (thinning of strata as an increase in burial depth, due to porosity loss) is a function of the lithology and the weight / thickness of the rock column above the layer at any given time. Genesis calculates from built-in empirical relationships (such as Athy's Law: Figure below) that are based on the formula:

$$Ø = Ø_0 \, e^{-cy}$$

Where $Ø$ is the surface porosity at any depth y, $Ø_0$ is the surface porosity and c is the coefficient that is dependent on lithology and describes the rate at which the exponential decrease in porosity takes place depth.

Porosity decrease with depth for sandstone and shale following Athy's Law: $\Phi = \Phi_O e^{-CZ}$



9.1.2 Heat flow through time:

A typical basin model solves for temperature from given heat flow and thermal conductivity. Thermal conductivity is assumed (given) for each different lithology and is a function of compaction. Heat flow may be deduced from present day temperature measurements and conductivity. The biggest uncertainty is heat flow through time.

Temperature of any material, including rocks, is proportional to the heat it retains. Heat tends to flow from higher temperature to lower temperature. So any temperature difference will cause heat to flow. There are basically three factors that control terrestrial heat flow: (1) the thickness of lithosphere. Since at the base it is always 1330 °C – a thinner lithosphere results in higher total heat flow, (2) the RHP (Radiogenic heat production) and thickness of crust (mostly from granites), which may account for up to 50% of the heat flow, and (3) the RHP from sediments, which is relatively small contribution, but may become significant when the sediment column is significant. For a given heat flow, lower conductivity (as in shale) will result in a higher thermal gradient. Thermal conductivity of rocks and fluids vary tremendously. Higher porosity also means lower bulk conductivity because fluids have much lower thermal conductivity than rock matrix. Carbonate rocks usually have higher conductivity than clastic rocks. Salts usually have the highest conductivity (Ungerer et al. 1990).

Rift basins are subject to highly variable and relatively high heat flows (McKenzie 1978; Pollack et al. 1993). The WOB is a complex polyphase rift basin, which has been heavily exhumed. Therefore (and within the aims of this research project), it is considered a reasonable approach for this study to model heat flow through time, by using a range of different geothermal cases through time (low, mid and high), that are based on analogue rift basins (e.g. Rhine rift system) and published estimates of paleo-geothermal gradients from Appetite-fission-track studies that have previously been conducted in the basin (e.g. Holford et al. 2010). These geothermal cases are simply input into the burial history plot, described above.

9.1.3 Modelling timing of hydrocarbon generation

Genesis uses the burial and thermal history in conjunction with specified (by the user) source-rock kinetic parameters to model timing of hydrocarbon generation. Source-rock kinetic reactions, such as kerogen to oil and gas conversion, is a function of kerogen type, temperature and time. Higher temperature results in faster reaction. The basic equation that Genesis uses implies that reaction rate dx/dt is:

$dx/dt = - A \cdot \exp(-E/RT) \cdot x$ where:

- x - concentration of material to react,
- A - frequency factor;
- E - activation energy,
- R - the gas constant,
- T - temperature

Genesis measures the extent of the reaction using a quantity called transformation ratio (TR) and to determine what fraction of the kerogen has already converted to hydrocarbons. If TR is plotted against geological time, then the timing of hydrocarbon generation can be inferred.

The kinetic parameters required to model source-rock transformation ratio within Genesis include: kerogen lithofacies, initial HI (hydrogen index) and TOC (total organic carbon content), for which this study uses published analogue values from (Marshall & Hewett 2003).