Jurassic Oceanic Gateways of the North Atlantic

Olivia April Walker

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Abstract

This thesis analyses two distinct data sets from West Iberia and the Norwegian North Sea, and aims to improve the understanding of ocean seaways, and associated strata, in the context of Mesozoic continental rifting of the North Atlantic Ocean.

For the West Iberian margin, reprocessed 2D seismic profiles, integrated with borehole data, unveil the emergence of a Jurassic seaway approximately 200 km wide. This period coincides with Triassic–Early Jurassic continental rifting, marked by substantial tectonic subsidence. For the first time, the research quantifies the thickness of Mesozoic syn-rift strata and West Iberian salt layers within deep-offshore basins, revealing a thickness variation from 1.7 km to 2.5 km. These findings, coupled with a substantial succession of Lower-Middle Jurassic strata, confirm the extension of the seaway from the Lusitanian Basin into present-day continental-slope basins. Backstripping analysis of Early Jurassic depocentres in West Iberia documents critical tectonic subsidence, leading to the segregation of the seaway into distinct sectors. The study estimates a total subsidence of approximately 5 km in the deep-offshore Peniche Basin during the Late Triassic-Early Jurassic, a notable contrast to the approximately 1.1 km recorded in the proximal Lusitanian Basin. The seismic-stratigraphic record from this time suggests a unified seaway between the Lusitanian and Peniche basins, with significant rift-shoulder exhumation occurring from the Late Jurassic onwards. Moreover, borehole stratigraphy across early Mesozoic basins in West Iberia, Newfoundland, and the North Sea reveals a tripartite depositional sequence of continental, evaporitic, and marine layers, indicative of a co-genetic evolution across the North Atlantic margin.

The analysis of the Norwegian Central Graben, conducted with data provided by IGI Ltd., evaluates some geochemical characteristics of source rocks during the Late Jurassic. This dataset, including kerogen types I, II, and III, along with supplemental biomarker analyses, serves as proxies for discerning terrestrial and marine organic matter during deposition phases. The findings indicate that the central North Sea's middle-upper Jurassic units possessed a heterogeneous geochemical signature, shaped by the fluctuating depositional environments typical of rifting. Notably, terrestrial organic matter is identified in various proportions within syn-rift strata, not wholly succeeded by marine organic matter as rifting advanced. Biomarker evidence corroborates the presence of mixed organic matter sources throughout the rifting.

In summary, comparisons of the seaways studied in this thesis make it clear that they both witnessed, during some part of their rifting history, salt deposition, with marine incursions present during and after the deposition of the latter. Basin isolation and limited connectivity between oceans gradually evolves into wider, and more connected ocean seaways as the early stages of continental rifting develop. Yet, biomarkers for the upper Jurassic of the Northern North Sea still reveal an important mixing of terrestrial and marine sources of kerogen, some 100 Ma after continental rifting was initiated in both West Iberia, the North Sea, and over the North Atlantic as a whole. As a corollary, this work shows that the presence of these mixed kerogen sources has constructive implications for resource exploration, particularly if the geochemical characteristics of the Northern North Sea are representative of the deep-offshore frontiers of the North Atlantic domain.

Author note and status of publications

One chapter presented in this thesis has been prepared as a scientific paper for publication in an international journal. The present status is as follows:

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Although the article is co-authored with the project supervisors, the work presented in the publication is that of the lead author, Olivia Walker. Editorial work was provided by the project supervisors in accordance with a normal thesis chapter.

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1 Contents

2 Review and Introduction

2.1 The significance and evolution of Oceanic Gateways

Seaways, marine gateways, or ocean seaways are critical components of Earth's oceanic and climatic systems. These natural passages connecting different ocean basins, play a crucial role in regulating global climate, ocean circulation, and marine biodiversity. The significance of these gateways lies in their ability to control the exchange of water masses, heat, salt, and nutrients between oceans, thereby influencing climatic conditions, sea levels, and ecological systems on a global scale.

The evolution of these oceanic seaways is intrinsically linked with the dynamic nature of Earth’s lithosphere. Through a multifaceted interaction of tectonic activities, sea level variations, and climate conditions, these gateways have formed, altered, and sometimes disappeared, leaving a profound imprint on the Earth’s climate and biosphere. Characterised by their genesis through extensive geological processes—such as flexural subsidence, subduction, collision, continental breakup, rifting, and drifting—with widths of hundred to thousands of kilometres and durations of tens to hundred of million years (Rossi et al., 2023). They can serve as persistent connectors between expansive basins and experience significant modifications in their width on shorter timescales due to sea-level fluctuations (Minor et al. 2022).

For instance, during Pangaea's disintegration, seaways like the Laurasian Seaway, (one of the focuses of this thesis) and the Hispanic Corridor emerged, illustrative of the development of vast seaways through a rift-to-drift evolution, morphing from constricted seaways on rifted continental crust to completely oceanic seaways (Ford and Golonka 2003; Dera et al. 2015; Porter et al. 2013; Ziegler 1988; Doré 1991; Bjerrum et al. 2001).

Meanwhile, the Cretaceous Western Interior Seaway, formed in a retro-arc foreland basin via the intricate interplay of flexural and dynamic subsidence tied to the subduction of the Farallon and Kula plates, facilitated a connection from the Arctic to the Gulf of Mexico during the Boreal Sea's southward transgression from the Early Cretaceous (DeCelles 2004; Liu and Nummedal 2004; Liu et al. 2014; Peng et al. 2022). Its closure at the Cretaceous end was attributed to a shift in subducted plate angle, modifying subsidence patterns and instigating Laramide-style uplifts, thereby ceasing the seaway's existence through an initial disconnection from the Boreal Sea and subsequent closure of the connection to the Gulf of Mexico, albeit the basin lingered as a constricting epicontinental sea until the Maastrichtian (Cross 1986; DeCelles 2004; Leva López and Steel 2015; Minor 2022; Minor et al. 2022).

Additionally, the Tethys Seaway, which provided a connection between the eastern proto-Mediterranean Sea and the Indo-Pacific Ocean mainly during the Eocene, gradually closed as a result of the collision between Arabia and Eurasia following oceanic crust subduction. Its final closure around 20 Ma, contemporaneous with a land animal migration, underscores how seaway closures can forge significant biological connections for terrestrial species (Allen and Armstrong 2008; Okay et al. 2010; Straume et al. 2020; Harzhauser et al. 2007).

The interplay between marine seaways and past global and regional environmental change forms a pivotal focus in much geological and paleoceanographic research. Through various lenses, diverse studies have unveiled the nuanced and sometimes dramatic consequences of seaway dynamics, facilitating a rich understanding of their complex interactions and implications on oceanic and climatic change phenomena. Many of the largest and most well researched seaways have been done so for their role in connecting various oceanic basins and therefore facilitating an interaction with distinct climatic zones throughout geological history. These seaways have primarily been regulated by hydrostatic sea-level differences, density disparities, and thermohaline circulation, which is driven by movements compensating for density differences attributed to temperature and salinity (Bjerrum et al. 2001).

Notable examples of these seaways include the Cretaceous Western Interior Seaway and the Laurasian Seaway, both of which enabled faunal migrations and were influenced by major geological events such as the development of the Atlantic Rift and substantial transgressions. These seaways not only facilitated migration routes for species but also were subject to, and subsequently influenced, climatic changes and biotic developments in their respective regions (Doré 1991; van de Schootbrugge et al. 2020; Korte et al. 2015).

During the Paleogene, the presence of the Northern–Central Eurasian Seaway, connecting the warm Paratethys waters to the colder paleo-Arctic waters, significantly influenced climate and biota, especially following its closure (Akhmetiev and Beniamovski 2009). A thorough review of the geological, stratigraphic, and paleoenvironmental evolution across various Central Eurasian basins provides valuable insights into the complex temporal and spatial reconstruction of the (proto-) Paratethys domain during the Paleocene–Eocene (Palcu and Krijgsman 2022). Alterations within the many seaways and marine passages connected to the Paratethys triggered notable variations in intrabasinal connectivity, thereby influencing regional hydrological budgets and facilitating the formation of anoxic bottom-water conditions within stratified water masses. Furthermore, through the Eocene–Oligocene transition, these seaways progressively closed, the closure of the Northern-Central Eurasian Seaway led to a disruption in polar-tropical water exchange. With each closure the Paratethys became incrementally more isolated culminating in its evolution into an anoxic giant for approximately 20 million years (Palcu and Krijgsman 2022).

Moreover, large east–west-oriented seaways, such as the Tethys Seaway, the Central American Seaway, and the Indonesian Seaway during the early Cenozoic, provided vital circum-global connections between different oceans, significantly influencing global oceanic circulation patterns and facilitating heat diffusion and biodiversity across various latitudes (Berggren and Hollister 1977; Straume et al. 2020). Notably, alterations like shallowing or closure of these seaways introduced profound changes to global current and heat-flow transport patterns, such as transitioning from primarily east–west to north–south pathways (Straume et al. 2020).

This intricate relationship between the opening and closure of oceanic seaways and global climate change provided the focal point for the research from Bahr et al. (2022) which drawing from various case studies demonstrated the profound changes driven by even minor alterations in ocean currents and gateways geometries.

The most critical aspect highlighted in the Bahr et al. (2022) review is the concept of gateways as "neuralgic points" in the global oceanic system. This concept implies that the strategic positioning of these gateways renders them drivers of climatic shifts. For example, during the Cenozoic era, the formation of ice sheets in both hemispheres is fundamentally linked to the dynamics of these gateways. The Tasman Gateway and Drake Passage, upon their opening, instigated extensive ice-sheet growth, exemplifying how gateway formation can have far-reaching climatic consequences.

Conversely, the closure or narrowing of gateways such as the Central American Seaway and the Indonesian Seaway mirrored similar climatic outcomes. Bahr et al. (2022) shows that these gateway alterations initiate significant reorganisations in oceanic heat and salt transport, subsequently transforming the global climate. This connection is especially notable considering the prolonged nature of tectonic changes that shape these gateways, often occurring over millions of years.

A case in point is the transformation of the Indonesian Seaway around 3.5–3 Ma. A relatively minor northward movement of New Guinea, around 2°–3° latitude, was sufficient to shift the source of subsurface waters flowing through it. This subtle geographical reconfiguration resulted in a considerable cooling of the thermocline in the Indian Ocean, illustrating the non-linear and sometimes abrupt nature of oceanic and climatic changes triggered by gateway dynamics.

However, the challenges in studying these phenomena are significant. Bahr et al. (2022) emphasise the difficulties in accurately constraining the palaeodepth and palaeogeography of ancient gateways, due to incomplete sedimentary successions resulting from erosion or tectonic deformation. These challenges necessitate reliance on indirect proxy data, including faunal exchange records, geochemical paleo-water-mass tracers like εNd, and proxies for palaeotemperature and palaeosalinity changes. Similarly, the effectiveness of numerical model simulations, crucial for accurate estimates of gateway configurations and climatic effects, depends on precise palaeogeographical representations. Given the complexity of seaways, which might include islands and narrow passages, achieving high spatial resolution in all three dimensions is difficult (Bahr et al, 2022).

2.2 The structural evolution of Continental Rift Basins

This section aims at providing a review of the structural and stratigraphic evolution of continental rift basins.

2.2.1 Introduction

Continental rift basin formation is a complex process influenced by various factors. The evolution of rift basins involves the extension and thinning of the continental lithosphere, leading to the development of fault systems and the subsequent formation and subsidence of topographical areas, also known as rift basins (Moeller et al., 2013). This process is a precursor to continental rupture, the formation of a mid-oceanic ridge and sea floor spreading leading to the eventual development of oceanic basins. Not all rifts, however, proceed to complete seafloor spreading, and some become inactive before new oceanic crust forms (e.g., Brun, 1999; Corti et al., 2003).

Numerous studies have been carried out to understand the cause and mode of lithospheric extension (e.g. Brun, 1999; Corti et al., 2003; Dewey and Hancock., 1987; Keen, 1985; Morgan and Baker, 1983; Ziegler, 1992) during continental rift. These include mantle plume activity, which results in uplift and thermal thinning of the lithosphere, gravitational potential energy variations, and far-field tectonic stresses.

Thinning may result from horizontal extension of the continental lithosphere with far-field stresses generated within or at boundaries of the lithosphere create the extensional field (Mckenzie, 1978). Thus, meaning the crust and lithospheric mantle are simultaneously stretched from the start of the rifting process (Fig 2.1). For example, rift basins can form at divergent plate boundaries, where two plates are moving apart, leading to extension and the formation of new ocean basins (Wong et al., 2023) The second may result from mantle plume activity acting as a heat source at the base of the lithosphere (Burke and Dewey, 1973) where the far-field stresses are related to 'slab-pull' mechanisms (Şengör and Natal'in, 2001) (Figure 2.1). Unlike the first mechanism, whilst the lithospheric mantle is thinned by thermal erosion the continental crust preserves original or approximate thickness, only following uplift and volcanism does the crust thin by extension in the final stage of deformation. These two mechanisms correspond to the concepts of 'passive' and 'active' rifting, respectively (Şengör and Burke, 1978) and can form in different settings. It is well known that many rifts display a combination of both passive and active mechanisms (Merle, 2011) and that can be further displayed through the global record of rift systems during Earth's history, not developing continuously but throughout successive phases of specific ages (Lamotte et al., 2015)

The presence of pre-existing structures and weaknesses in the crust also plays a role in rift basin formation (Figure 2.1). These structures can influence the localisation of extension and the development of rift systems (Gordon et al., 2012). Additionally, the rheological properties of the crust can affect the style and rate of extension, leading to variations in rift basin formation (Gordon et al., 2012). The sedimentary infilling of rift basins is another important factor. Sedimentation occurs within rift basins as a result of erosion and deposition processes. Sediments are transported and deposited in response to the topographic and hydrological conditions within the basin (Pavelić, 2001). The deposition of sediments can contribute to the subsidence of the basin and influence the stratigraphic architecture of the rift fill (Pavelić, 2001). As well as this, the extension of the lithosphere results in the development of normal faults, which in turn control the geometry and subsidence of the resulting basin (Péron-Pinvidic et al., 2007).

This amalgamation of parameters yields a rich diversity in rift formations. For instance, there are distinctions to be found in rift dimensions, where some rifts, like the East African Rift or the Cenozoic European Rift, are narrower, as opposed to others, like the Basin and Range province or the Aegean extensional area, which exhibit a width surpassing the lithospheric thickness (Brun, 1999; Buck, 1991). Similarly, variations occur in the form of asymmetric versus symmetric extensions on crustal or lithospheric scales, which have been explored by researchers such as Keen et al. (1987), Morgan and Baker (1983), and Wernicke (1981). Furthermore, there are notable differences between magmatic rifts and notably non-magmatic rifts, a subject explored by Perez-Gussinye and Reston (2001).

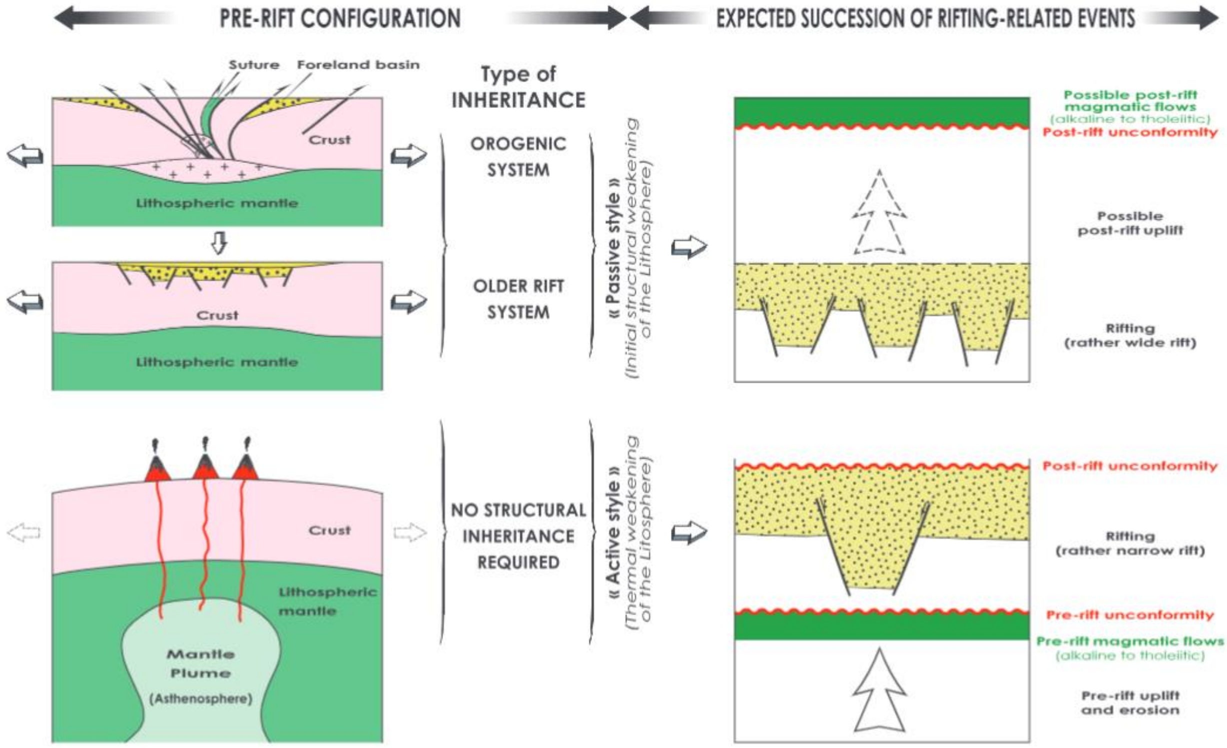


Figure 2.1: Adapted from Lamotte et al. (2015), this diagram offers a detailed comparative illustration of the key factors distinguishing active and passive rifting styles. On the left, the pre-rift configuration is depicted, while the right side delineates the sequence of events during rifting in both passive and active contexts. Notably, a plume is a precursor in active rifting, but extensional forces, as described by Burov and Gerya (2014), are also essential for rift development. The central distinction lies in the nature of lithospheric weakening: mechanical weakness due to structural inheritance indicates passive rifting, whereas thermal-origin weakness signifies active rifting.

This diverse array of rift manifestations reveals the interplay of multiple factors in shaping the distinct characteristics of lithospheric deformations. This is discussed in Merle (2011) work on classifying continental rift. Globally therefore, the continental rift basins that reflect this interplay of factors are present in various geographical and tectonic settings today and have been in the past.

The East African Rift System (EARS) is an example of an active continental rift, showcasing the early stages of continental breakup. This rift system extends from the Afar Triple Junction in the north to Mozambique in the south and is marked by the divergence of the Nubian and Somali Plates. Volcanic activity, sedimentation processes, and the development of half-graben structures are characteristic features of this rift (Chorowicz, 2005).

Similarly, the Basin and Range Province in the western United States exemplifies a continental rift basin characterised by elongated mountain ranges separated by down-dropped valleys or basins. The extensional tectonics in this region are associated with the eastward movement of the Pacific Plate and the relative westward movement of the North American Plate (Brun. 1999).

The Rhine Rift Valley in Europe is another notable example, formed as a result of the Alpine orogeny and characterised by a series of graben structures filled with sedimentary sequences. The formation of this rift has been influenced by the reactivation of ancient fault systems and variations in lithospheric strength (Ziegler & Dèzes, 2007).

2.2.2 Rift basin architecture

Rift architecture in continental rift basins is a complex and dynamic process influenced by various factors such as the distribution of faults, the arrangement of sedimentary layers, the presence of volcanic activity, and the tectonic forces driving the rift. These processes play a significant role in shaping the geometry and distribution of rift basins**.**

The structural elements that define rift architecture include horsts and grabens, accommodation zones, half-grabens, and relay ramps, among others. Horst and grabens are defined as alternating uplifted and down-dropped blocks of crust generated by extensional forces and defined by bounding faults (Buck, 1991). The development of these structures accommodates the extension of the lithosphere and results in the characteristic topography of rifted landscapes. Accommodation zones are complex regions of deformation that connect and transfer extension between individual fault segments or systems (Ferrill et al., 1999). Relay ramps, on the other hand, are topographic depressions that form between overlapping fault segments and facilitate fault linkage and the transfer of slip (Peacock & Sanderson, 1994). The progressive extension of the lithosphere leads to the formation of asymmetric half-grabens and symmetric full-grabens, characterised by their distinct faulting and sedimentary fill patterns (Gibbs, 1984). These structures record the extensional history of the basin and influence the spatial distribution of sedimentation and volcanic activity. Volcanic activity during rifting can lead to the formation of volcanic edifices, lava plateaus, and igneous intrusions (Ebinger, 2005). The interplay between volcanic and sedimentary processes contributes to the stratigraphic complexity of rift basins, with the deposition of alluvial, fluvial, lacustrine, and aeolian sediments recording environmental changes and tectonic activity (Prosser, 1993).

2.2.3 Fault Linkage Models

Gawthorpe & Leeder (2000) emphasise the importance of fault propagation, growth, linkage, and death in controlling basin architecture during the evolution of active basins. Understanding the models of fault linkage is pivotal in unravelling the geometric and kinematic evolution of continental rift basins. The work of Gawthorpe & Leeder (2000) is seminal in this context, proposing models that elucidate how faults initiate, propagate, and eventually link to accommodate extension. Highlighted in Figure 2.2, a 3D schematic model from their research shows the evolution of a normal fault array during the stages of fault initiation, fault interaction and linkage and finally of through-going fault zones. Figure 2.2A shows a large number of small displacement fault segments with low surface topography influenced by fault propagation faults and surface-breaking normal fault scarps. Figure 2.2B shows faults interacting and linking, where stress feedback between segments influence growth, and deformation in the fault array begins to become localised along the major fault zones of A,B,C. Faults in stress shadows begin to become inactive e.g. C. Figure 2.2C shows deformation localised along what is now major border fault zones (e.g. 1, 2, 3) giving rise to half-graben and graben depocentres.

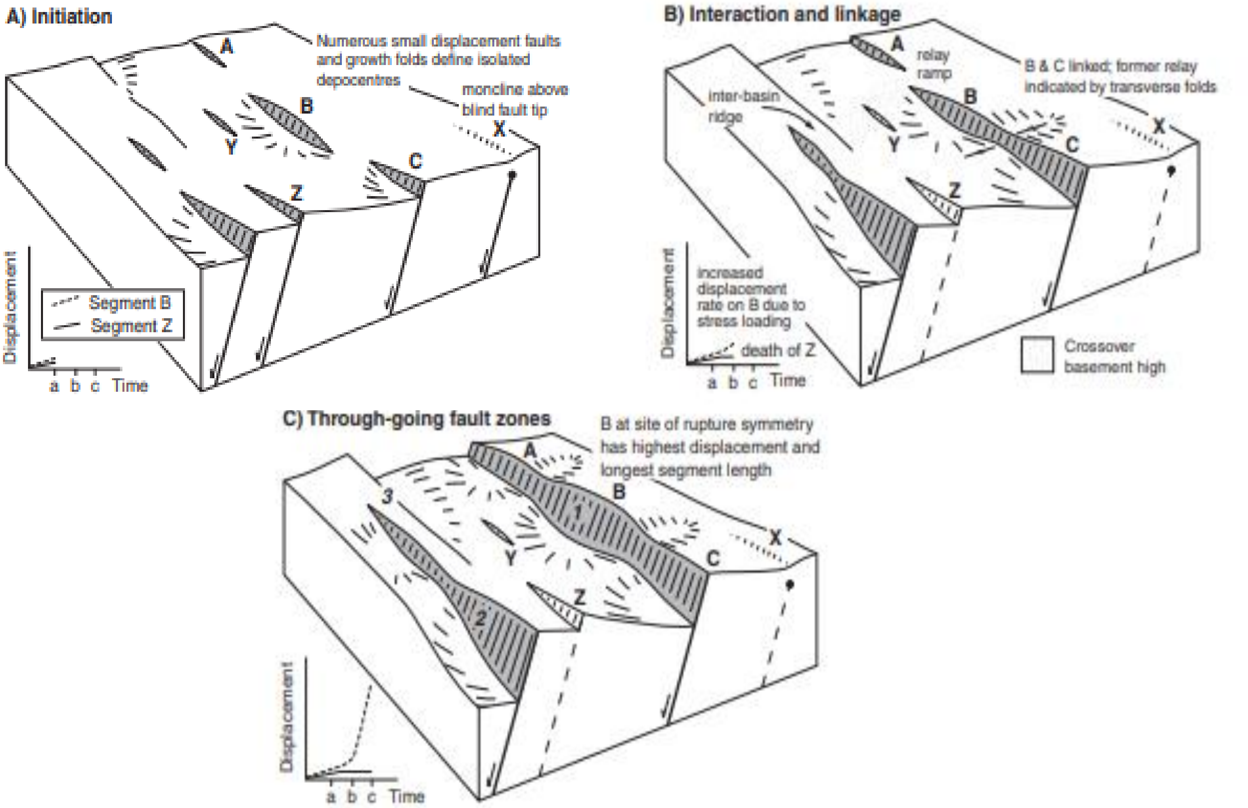


Figure 2.2: Evolution of a Normal Fault Array in Three Stages frm Gawthorpe and Leeder (2000). 2.2A (Initiation): Illustrates the initiation stage with numerous small displacement fault segments and subtle topographic expressions marked by fault propagation folds and surface-breaking normal fault scarps. 2.2B (Interaction and Linkage): Demonstrates the interaction and linkage stage, where increased displacement on segment B due to stress loading leads to the inactivity of segment Z, and deformation begins to localize along the major fault zones A, B, and C. 2.2C (Through-going Fault Zones): Represents the advanced stage where deformation is highly localised along major border fault zones labeled 1, 2, and 3, with the formation of half-graben and graben depocenters, and the highest displacement along the longest fault segment B.

Trudgill & Cartwright (1994) introduced the concepts of hard-linkage and soft-linkage to describe the interaction and connection between individual fault segments. Hard-linkage refers to the physical connection of fault segments, while soft-linkage denotes the influence of stress and strain fields of neighbouring fault segments on one another, even if not physically connected. Fault segments can grow through a combination of lengthening and increasing displacement. The interaction of these segments is dependent on the spacing between them, their propagation rates, and the angle at which they propagate towards each other (Walsh et al., 1999). The linkage of these segments influences the overall fault length, displacement, and throw, which in turn, affect the morphology and stratigraphy of the rift basin. As fault segments approach one another, they may form relay ramps. Eventually, these relay ramps may be breached, resulting in a through-going fault, a process well-documented by Withjack et al. (2002).

2.2.4 Strain Localisation

Strain localisation refers to the phenomenon where deformation, including stretching, shortening, and displacement, is concentrated in localised zones within the lithosphere, leaving surrounding regions relatively undeformed. Cowie et al., 2005 discuss the spatio-temporal evolution of strain accumulation in Late Jurassic rifting in the northern North Sea, providing insights into the importance of strain localisation in rift systems. Cowie et al. (2005) highlighted the importance of the growth and linkage of faults in controlling strain localisation. Strain localisation is often manifested by the migration of fault activity and the development of fault networks. This process is driven by various factors, including the mechanical properties of the rocks, the presence of pre-existing structures, and the stress distribution within the lithosphere. As strain accumulates, it becomes concentrated along localised zones of weakness, such as faults or shear zones (Cowie et al., 2005). The importance of strain localisation lies in its role in accommodating deformation within the Earth's crust. It allows for the localisation of strain into discrete zones, which can result in the development of distinct geological structures, such as fault systems, folds, and shear zones. The rate at which stress is applied and the rate of strain accumulation are also critical factors influencing strain localisation. Variations in these rates can lead to the development of different deformation structures, including faulting, folding, and ductile flow (Mancktelow, 1999).

The mechanisms behind strain localisation are diverse and can include processes such as shear heating, grain size reduction, and mechanical anisotropy. Heterogeneity in rock strength and mechanical properties contributes to the uneven distribution of strain, with deformation preferentially localised in weaker zones (Bürgmann et al., 1994). Understanding strain localisation is crucial for modelling and predicting the behaviour of rocks under deformation. It allows for the development of more accurate geological models and helps in assessing the mechanical behaviour and stability of geological structures.

2.3 The stratigraphic evolution of Continental Rift Basins

The stratigraphic evolution of continental rift basins is inherently tied to their structural development, sedimentary processes, and climatic conditions. The study of rift basin stratigraphy provides insights into the temporal and spatial changes in sedimentation, basin subsidence, and the influence of tectonics and climate on depositional environments.

Variations in precipitation, temperature, and sea level alter the sediment supply, depositional environments, and the type of sediments deposited (Nichols & Fisher, 2007). For instance, increased precipitation may enhance erosion and sediment supply, while changes in sea level can alter the base level, affecting sedimentary processes across the basin. The interplay between climate and tectonics is critical in deciphering the unique stratigraphic sequences and depositional history of rift basins.

2.3.1 Seismo-Stratigraphic Models, Prosser (1993)

Prosser (1993), highlighted the seismic expression of rift-related linked depositional systems. They explored how interconnected stratigraphic units, responding to fault activity, illustrate the dynamic nature of rift basins. Prosser's work underscored the importance of understanding seismic data to interpret the interaction between faulting and sedimentation and its imprint on the basin stratigraphy.

Their findings showed that there may be a common expression of tectonic control behind many rift basin stratigraphies through a four-fold model for half-graben type (fault bounding) basins. This being: 1. rift initiation 2. rift climax 3. immediate post-rift and 4. late post-rift stages of basin evolution that can characterise most basin infill stratigraphies, with associated systems tracts (linked depositional systems) which can vary according to climate, source rock composition, position relative to sea-level and eustatic fluctuations (Figure 2.3). It is by correlating these linked depositional systems with a particular tectonic systems tract that Prosser developed these models of basin evolution.

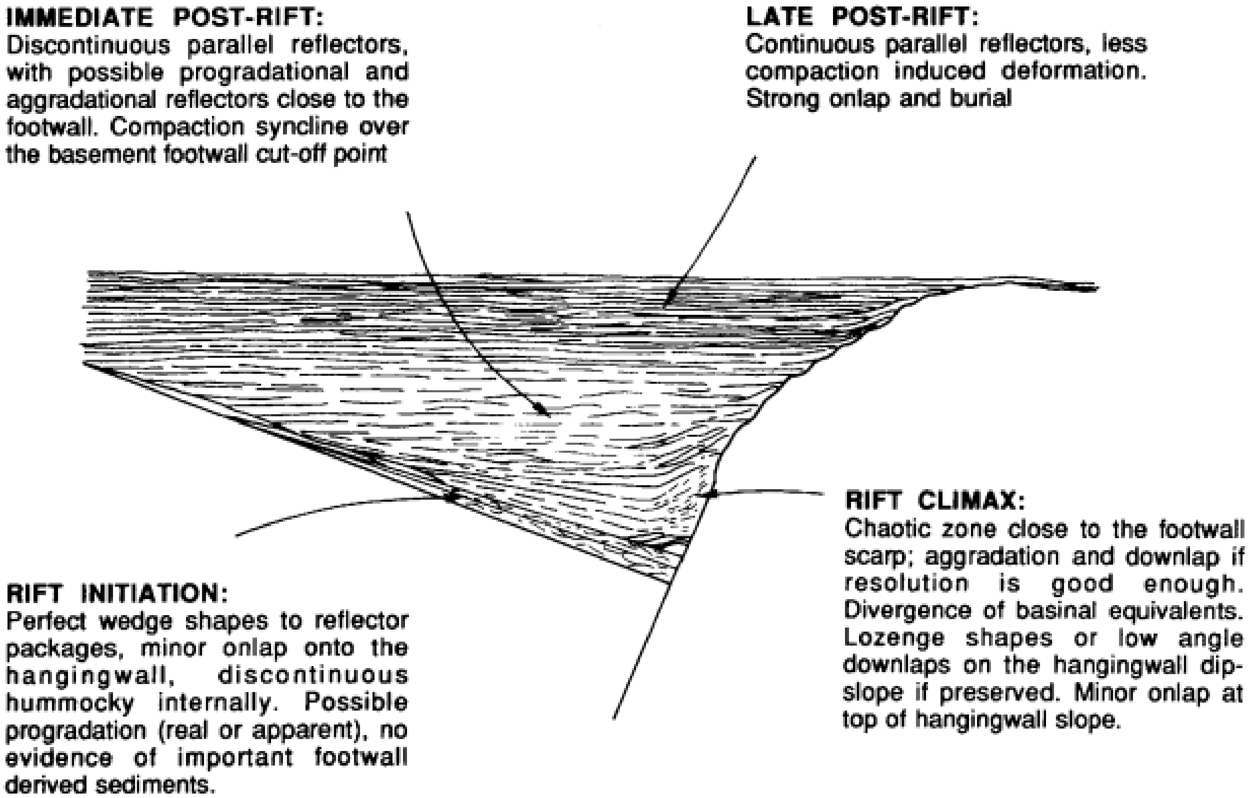


Figure 2.3: An idealised sketch section of a line drawing of a seismic section through an ideal basin where each tectonic systems tract can be identified from Prosser (1993) Author notes this is for summary purposes and characteric seismic expressions may not be present.

Rift Initiation (Prosser, 1993)

In the Prosser (1993) model rift initiation, or S2, is the first stage of movement on a fault that results in a depression in the crust's surface. This leads to the response of gravity-driven sedimentary systems. The basin is presumed to be subaerial at this stage, with enough water supply to maintain perennial fluvial systems, and the surrounding source areas are composed of consolidated, competent rock (Figure 2.4a). Variations from this situation will result in different depositional mechanisms and types of facies that accumulate. Therefore, an intricate understanding of the strata's physical relationships becomes critical to accurately identify the presence of the systems tract associated with rift initiation. The seismic sections from Prosser (1993) reveal a wedge-shaped geometry in the sequences associated with rift initiation, with internal reflector characteristics that are predominantly hummocky and discontinuous (Figure 2.3). This specific seismic signature suggests a scenario wherein sedimentation and subsidence are occurring at a balanced rate, resulting in the formation of superimposed wedge-shaped geometries.

Moreover, the formation of a depression in the pre-rift landscape brings about significant geomorphological changes, as highlighted by Prosser (1993). This results in the creation of a new depocentre, attracting gravity-driven depositional systems, and forming potential source areas for sediment at the footwall and hangingwall crests (Figure 2.4a). However, the model emphasises that the primary contributors to basin filling are not the immediate topographic highs, but rather streams from older, more established source areas with extensive drainage basins. These streams are rapidly redirected to the new basin, supplying fine, mature sediment, through axially positioned fluvial channels (Figure 2.4b).

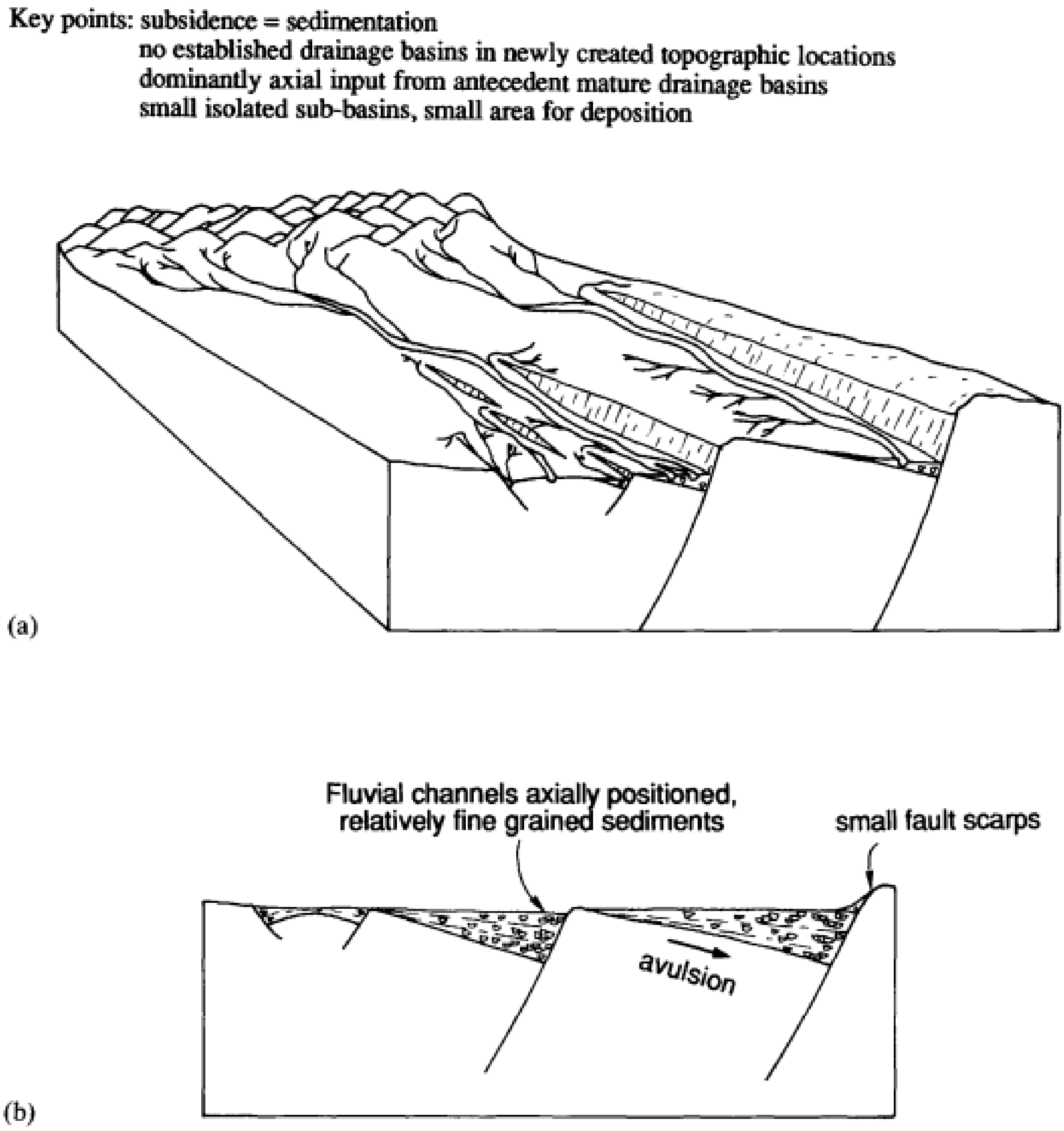


Figure 2.4: Rift Initiation systems tract (a) generalised block diagram showing longitudinal position of major depositional system; (b) schematic cross section shows small localised nature of fault-bounded basins, and small relief of new fault scarps (Prosser, 1993)

Rift Climax (S3) (Prosser, 1993)

This stage is characterised by the maximum rate of fault displacement, leading to pronounced subsidence and the creation of differential relief across fault scarps. The sedimentation during this phase often lags behind the subsidence, resulting in basin drowning (Figure 2.5a).

The seismic expression of the rift climax is marked by an increase in aggradation and the development of divergent strata, indicative of ongoing tilting of the hanging wall (Figure 2.3). The proximity to fault planes, however, can obscure detailed reflector geometries. High-quality seismic data is essential for identifying features such as footwall-derived fans and talus, although chaotic zones near the footwall may represent coarse-grained rock falls and talus without ordered bedding, making it challenging to generate reflections (Figure 2.5b). In basinward positions, the contrast in lithology between fans and lacustrine/marine deposits can lead to inter-bedding of horizons with strongly contrasting lithologies, facilitating the generation of reflections (Prosser, 1993).

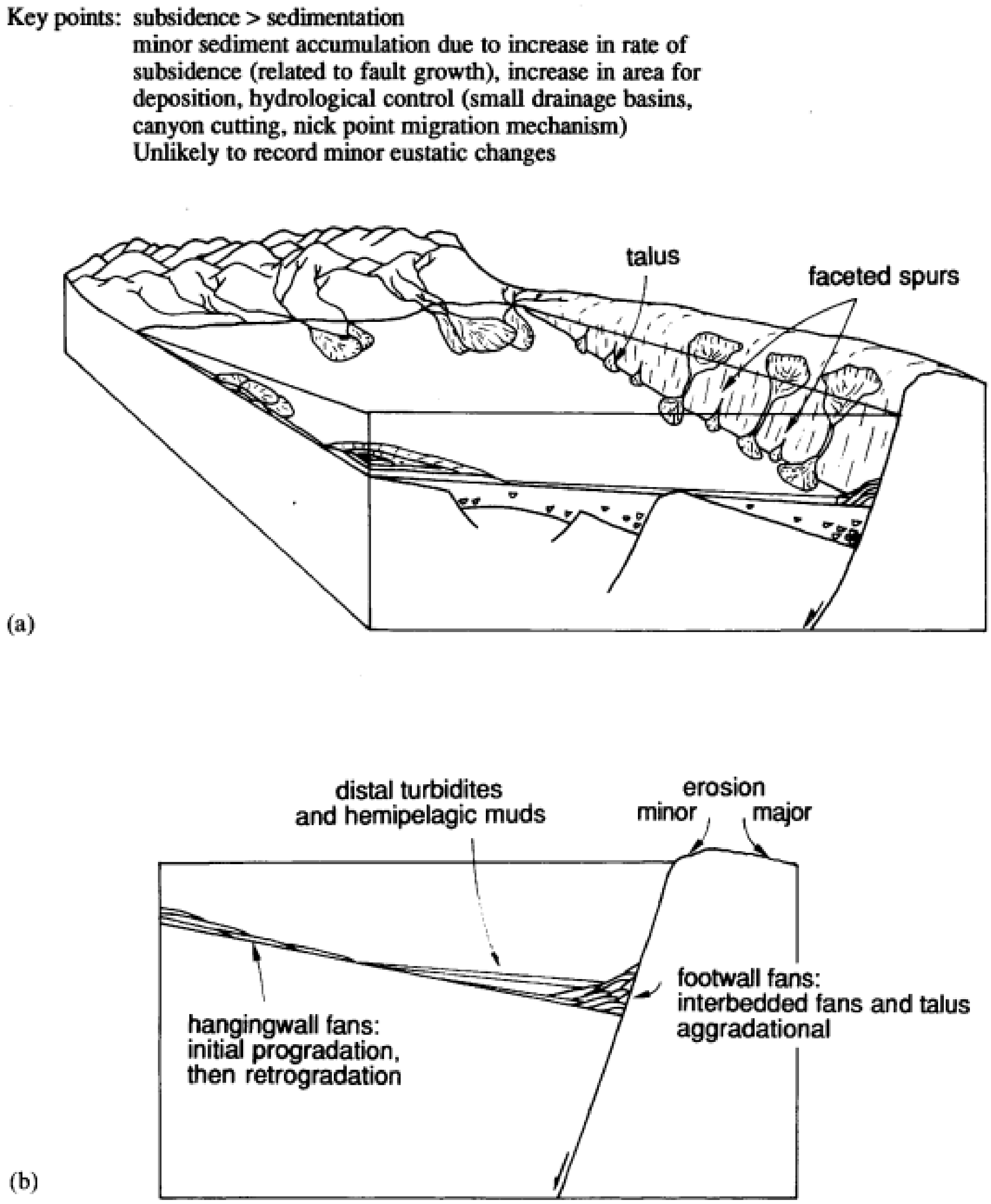


Figure 2.5: Rift climax systems tract (a) generalised block diagram shows increases area of deposition and small size of consequent drainage basins; (b) schematic cross section shows large relief on a single dominant fault plane (Prosser, 1993). Note this sketch represents late stage in climax of rifting when hangingwall has been transgressed and submerged.

The rift climax stage encompasses a range of depositional systems, all of which indicate seismic triggering. From rock falls and debris flows to dewatering features and slumping, the presence of soft sediment deformation structures is a feature of this stage.

1. Early Rift Climax Systems Tract: This is associated with aggrading reflectors close to the footwall and progradation and offlap from the hangingwall This stage is marked by the development of differential topography across the fault scarp, potentially leading to basin starvation. Sedimentary features include lacustrine or marine gulf environments near to the fault plane, with finer-grained sediments compared to the coarser footwall and hangingwall-derived deposits. Hangingwall-derived deposits are likely influenced by gravity, resulting in lobe-shaped geometries such as alluvial fans in subaerial settings and shoal-type deltas in subaqueous environments (Figure 2.6a).

2. Mid-Rift Climax Systems Tract: The onset of this stage is characterised by a change to retrogradational geometries and a fundamental shift in sediment transport dynamics. The drowning of earlier deposits leads to the development of linear facies belts such as long-shore bars and beach barrier systems. While the hangingwall slope initially has a greater potential for sediment supply, footwall sources often become more significant as the stage progresses (figure 2.6b).

3. Late Rift Climax Systems Tract: This stage is associated with a fully submerged environment, with low rates of sediment supply. Fine-grained siliciclastics dominate, blanketing the asymmetric basin topography. (Figure 2.5b & 2.6c).

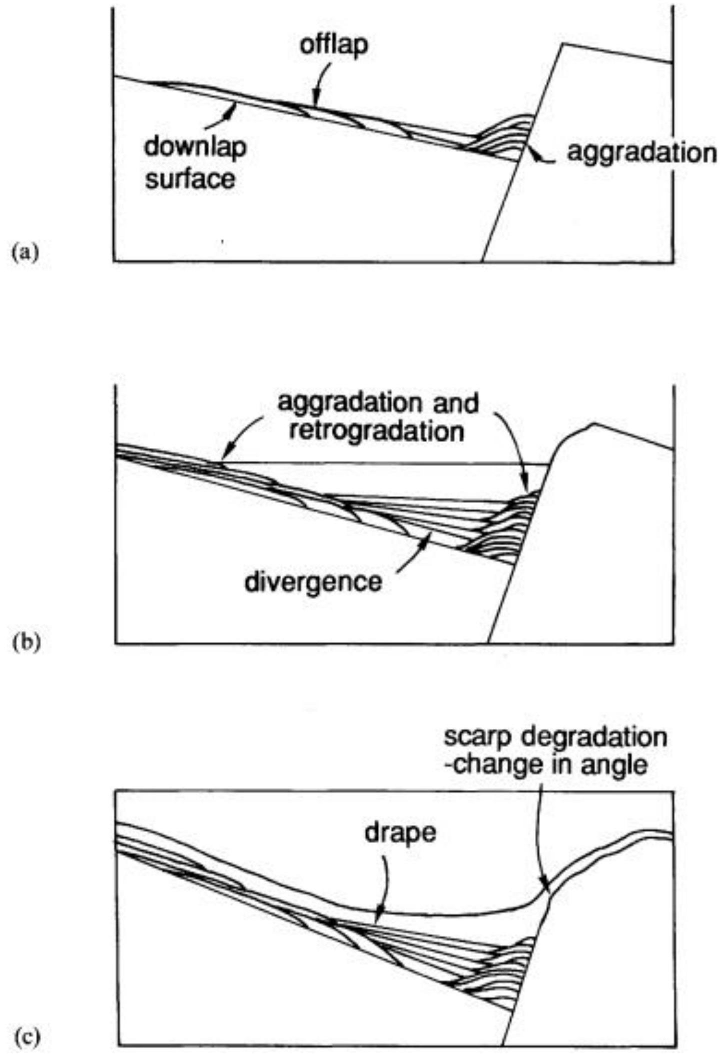


Figure 2.6: Possible reflector configurations of early, mid and late stages of rift climax systems tract. Tilting and divergence common at each stage. (a) early rift climax, (b) mid-rift climax, (c) Late rift climax. From Prosser (1993).

Immediate Post-Rift (Prosser, 1993)

This phase is characterised by the cessation of tectonic activities, particularly the stopping of displacement along the basin-bounding fault, which imparts a profound impact on the systems tract characteristics. Prosser (1993) dissects this phase into two main facets: (a) tilting of the hanging wall and differential subsidence across the fault place ceases and (b) a noticeable deceleration in the rate of regional subsidence, albeit with a continuation due to the ongoing effects of lithospheric thermal cooling. This change in the tectonic regime at the base of this stage produces a tectonically-generated onlap surface (Figure 2.7b).

During this time, the influence of eustatic sea-level changes becomes more pronounced, exerting a greater control over the finer-scale sedimentary features and stratal packages within the basin. This shift is starkly contrasted against the previous rift climax phase, where active faulting played a dominant role. A visual representation of these changes and the main characteristics of the immediate post-rift systems tracts is shown in Figure 2.7.

Key points: subsidence < sedimentation
increase in general grain size due to expansion of footwall drainage basins, increase in progradation, filled to spill point. More likely to record minor eustatic changes.

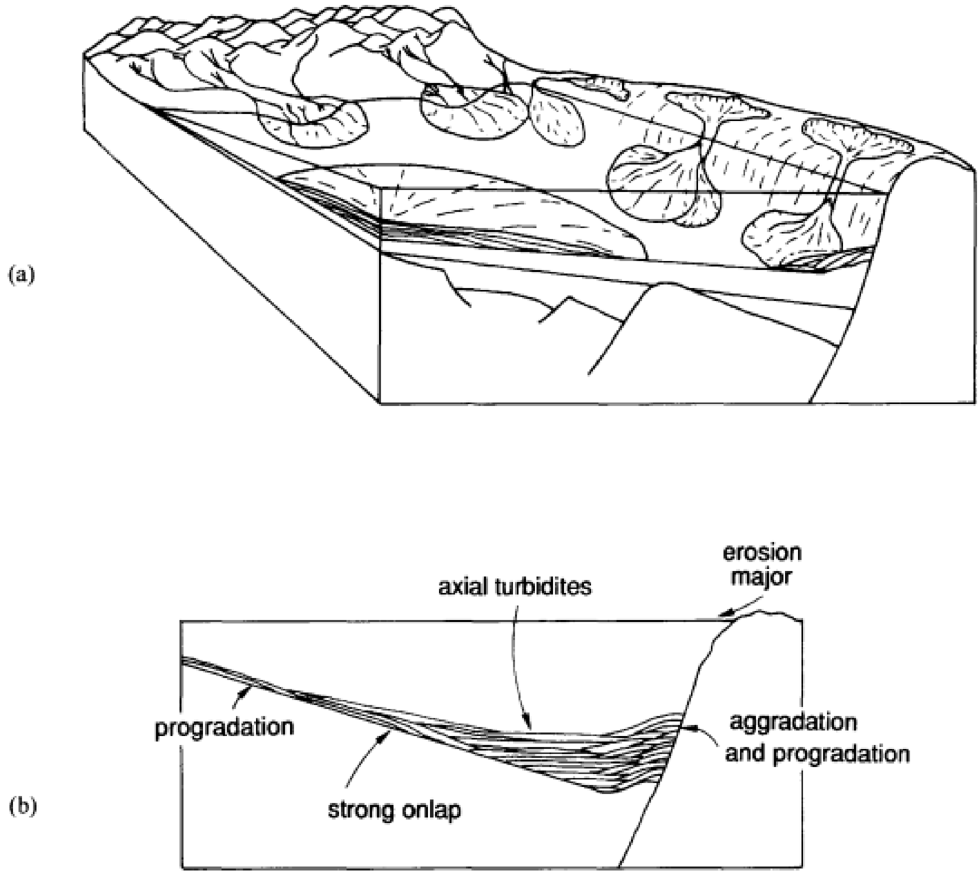


Figure 2.7: Immediate post-rift systems tract (a) generalised block diagram; (b) schematic cross section shows expansion and down-cutting of drainage basins, aggradation of facies through infillinf, prominent onlap surface and progration of sediment into basin from transverse as well as longitudinal systems (Prosser, 1993).

The seismic expression of this stage is marked by the end of both tilting and the creation of divergent reflector packages (Figure 2.3). The succeeding reflectors may show a continuation of the preceding aggradation initially as they infill the depression, but may show a greater proportion of associated progradation also. The lower boundary that marks this systems tract may, therefore, be a downlap surface in the centre of the basin, and a strong onlap surface updip on the hanging wall dip slope and the footwall scarp slope. The continuity and nature of the seismic reflectors during this phase may offer insights into the depositional energy, which is closely tied to the relief across the now-inactive fault scarp.

The characteristic linked depositional systems associated with this phase involve deposition infilling the basin, although regional subsidence may prevent this from happening and cause further drowning and reduction in sediment supply. Generally, however, with the reduction in subsidence the basin may become infilled or may be slowly infilled depending on if the drainage basin is in a subaerial or submarine position (Figure 2.7b).

Late Post-rift stage (Prosser, 1993)

From a seismic standpoint, the late post-rift systems tract is identifiable by its parallel and continuous reflectors, showcasing an onlapping pattern on the hanging wall dip slope and the eroded fault scarp. The boundary between the upper and lower systems tracts may be a surface with concordant reflectors on either side, but a change in reflector characteristics may indicate the waning influence of tectonics on sedimentation. The characteristic linked depositional systems of this stage involve erosion and degradation of the local source area leading to a fining of the sediment grain size through time.

2.4 The North Atlantic Ocean Domain

Encompassed by Europe and North America to the north, South America to the south, and Northwest Africa to the east, the North Atlantic Ocean occupies a pivotal position on the Earth's surface. Its expansive waters cover a crucial part of the mid-Atlantic region, hosting the Mid-Atlantic Ridge, a prominent underwater mountain range that marks the boundary between the North American and Eurasian tectonic plates to the north, and the South American and African plates to the south (Figure 2.8). This ridge is a site of divergent plate boundaries, where the tectonic plates are gradually moving apart, leading to the formation of new oceanic crust.

To the west, the ocean's basin interacts with the passive continental margin of North America, characterized by a broad continental shelf and a lack of significant tectonic activity. Similarly, to the northeast, the basin meets the passive margin of Northwestern Europe. Both of these passive margins are the remnants of ancient rifting that first led to the opening of the Atlantic Ocean, and the main focus of this thesis. On the other hand, the ocean's eastern boundary and it's interaction with the African plate is defined by a more complex interplay of tectonic that includes transform faulting, convergent boundaries and subduction zones as well as rift valleys.

Boasting an irregular coastline, the North Atlantic Ocean is home to numerous bays, gulfs, seas, and marginal islands, as illustrated in Figure 2.8. Among the noteworthy inlets are the Bay of Fundy, known for having the world's highest tidal range, the resource-rich North Sea, the deep Norwegian Sea, and the ecologically significant Gulf of Mexico. The ocean also shelters an assortment of islands, each with unique geological origins. Great Britain and Newfoundland, for instance, share a similar ancient geological heritage, whereas Iceland stands out as a product of more recent volcanic activity, situated on the Mid-Atlantic Ridge where the North American and Eurasian plates are drifting apart. In contrast, the Canary Islands, situated off the northwest coast of Africa, owe their existence to volcanic activity; they are relatively young in geological terms, having formed around 20 to 30 million years ago (Anguita & Hernán, 2000).

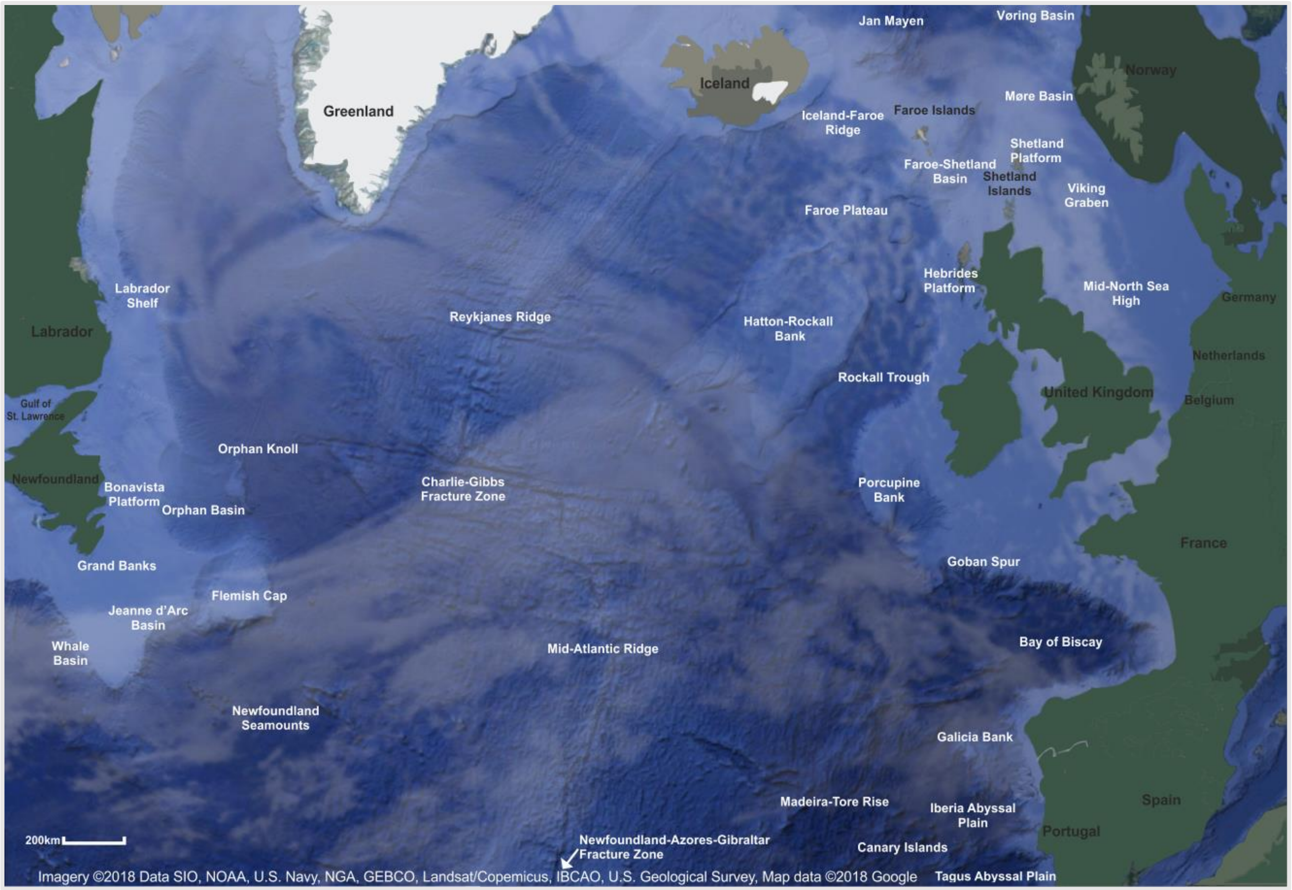


Figure 2.8: Map of North Atlantic Ocean highlighting the present day bathymetric features, continental shelf, basins, islands, and coastlines. Figure modified from Google Maps, 2018. Cardiff University, Google Maps [online].

2.4.1 Mesozoic rift systems of The North Atlantic

The North Atlantic opened along a series of spreading ridges that were separated by large transform faults, e.g. the Charlie Gibbs Fracture Zone and the Newfoundland-Azores-Gibraltar fracture zone, leaving behind a series of rifted basins and broadened continental shelves on its margins (Nirrengarten et al., 2018) (Figure 2.8). In the past, problems with plate reconstructions of the North Atlantic occurred in areas lacking obvious magnetic anomalies (Roberts et al., 1999), for example, offshore the Lusitanian Basin of Portugal and the Grand Banks of Canada there were uncertainties whether they were underlain by oceanic or continental crust. (Olivet, 1996). Since then, refraction data has shown that the Vøring Plateau, Møre-Faroe-Shetland Basins, the Rockall Trough, the Labrador Sea, the Orphan Basin, offshore Portugal and the Bay of Biscay are all in fact underlain by highly stretched continental crust (Avedik et al., 1982; Keen et al., 1987; Chian et al., 1995; Avendonk et al., 2006).

The opening of the North Atlantic was part of a larger tectonic process that involved the breakup of the supercontinent Pangea. It represents the final dispersal and end of the Laurasia continental amalgamation that formed the northern portion of the Pangaea supercontinent (Gaina et al., 2009; Hansen et al., 2009; Frizon De Lamotte et al., 2015; Peace et al., 2019) Pangea existed between Carboniferous and Late Triassic times (Ziegler, 1990) and was inherently unstable as the assembly of the supercontinent and the beginnings of its rifting were virtually simultaneous (Doré et al., 1991). Continental rifting began in the Early Permian, later resulting in the separation of Gondwana to the south and Laurasia to the North, and continued through to the Late Permian- Early Triassic (Siedler et al., 2004).

The influence of pre-existing crustal structures in the Pangea basement fabric , such as that from the Caledonian and Variscan orogenies, impacted the architecture and timing of the North Atlantic rift system (Chenin et al., 2015). The Caledonian Orogeny occurred in the latest Silurian-Devonian and was responsible for the amalgamation of terranes with different crustal compositions in the area. Following that, the Variscan Orogeny in the latest Carboniferous times superimposed more structural elements to the basement terranes as the supercontinent Pangea emerged (Stampfli et al. 2002). This combination resulted in a complex basement of different structural fabrics and compositions that ultimately had a close control on the location and orientation of the subsequent rift axes and rift basins (Naylor and Shannon., 2005).

The region west of Mid-Norway down to the west of Ireland is underlain by Caledonian basement with major structures striking NE-SW to N-S. Further south into Iberia, North America and Canada, the basement was affected by the Variscan orogeny and major structures strike E-W (Redfern et al., 2010) (Figure 2.9). Reactivation of these structures in subsequent continental rifting episodes gave rise to many basin defining features in the southern north Atlantic region (Coward, 1990). Research by Chenin et al. (2016) and Nirrengarten et al. (2018) have also shown that, in the northern North Atlantic, rifting followed the Caledonian Iapetus suture between Greenland and Norway whereas in contrast, both the northward and westward propagating rift arms disregarded the Variscan sutures in the southern North Atlantic.

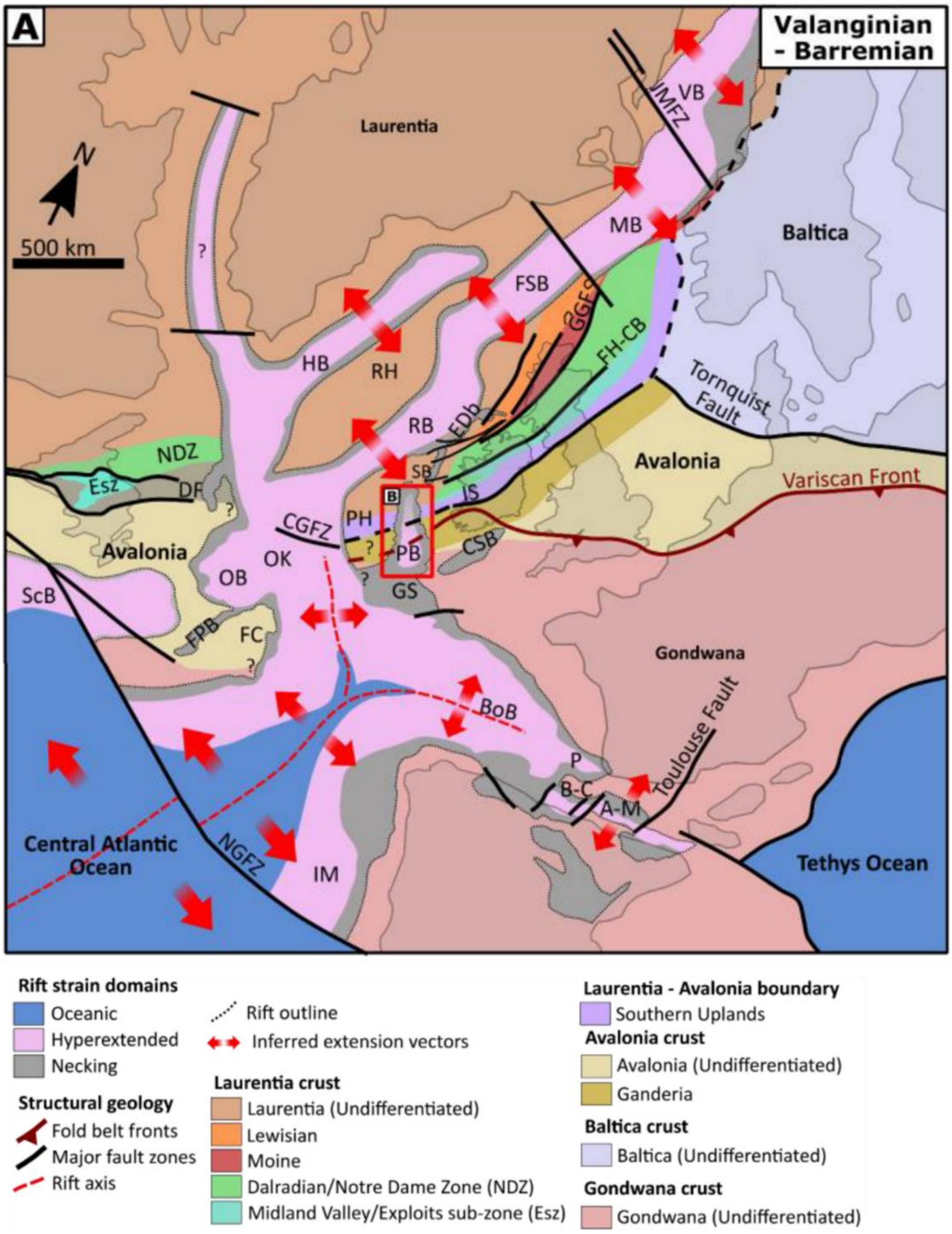


Figure 2.9: Palaeogeographic reconstruction of the proto-North Atlantic Ocean during the Valanginian-Barremian. Figure modified from Whiting et al. (2020) based on work see references within.

It is widely considered that the rifting occurring in the North Atlantic, leading to the opening of the North Atlantic Ocean, comprised two separate rift systems; one in the northern North Atlantic propagating south, often called the Arctic rift or the Northeast Atlantic rift, and the second occurring in the Central Atlantic propagating north into the southern North Atlantic propagating north more widely referred to as the ‘Atlantic rift’ moving initially into the Labrador Sea-Baffin Bay rift system and then into the North Atlantic (Srivastava, 1978; Doré et al, 2008).

. It is considered by many authors that these rifts were both formed by polyphase extension comprising at least several extensional ‘pulses’ from the Late Triassic to Early Jurassic (Roberts et al., 1999; Brikiatis, 2016; Siedler et al., 2004, Alves and Cunha, 2018). Both rifts are associated with the subsequent break-up of Laurasia, which included the continental plates of North America, Laurentia-Greenland, Iberia and Eurasia. This multiphase extension recorded the first Mesozoic extensional phases that affected the Eurasian-American domain from the Permian to the late Early Jurassic (Arthaud and Matte, 1977). It was during these two propagating continental rifting stages in the north Atlantic region that seaways developed as rifts widened and oceanic realms begin to connect.

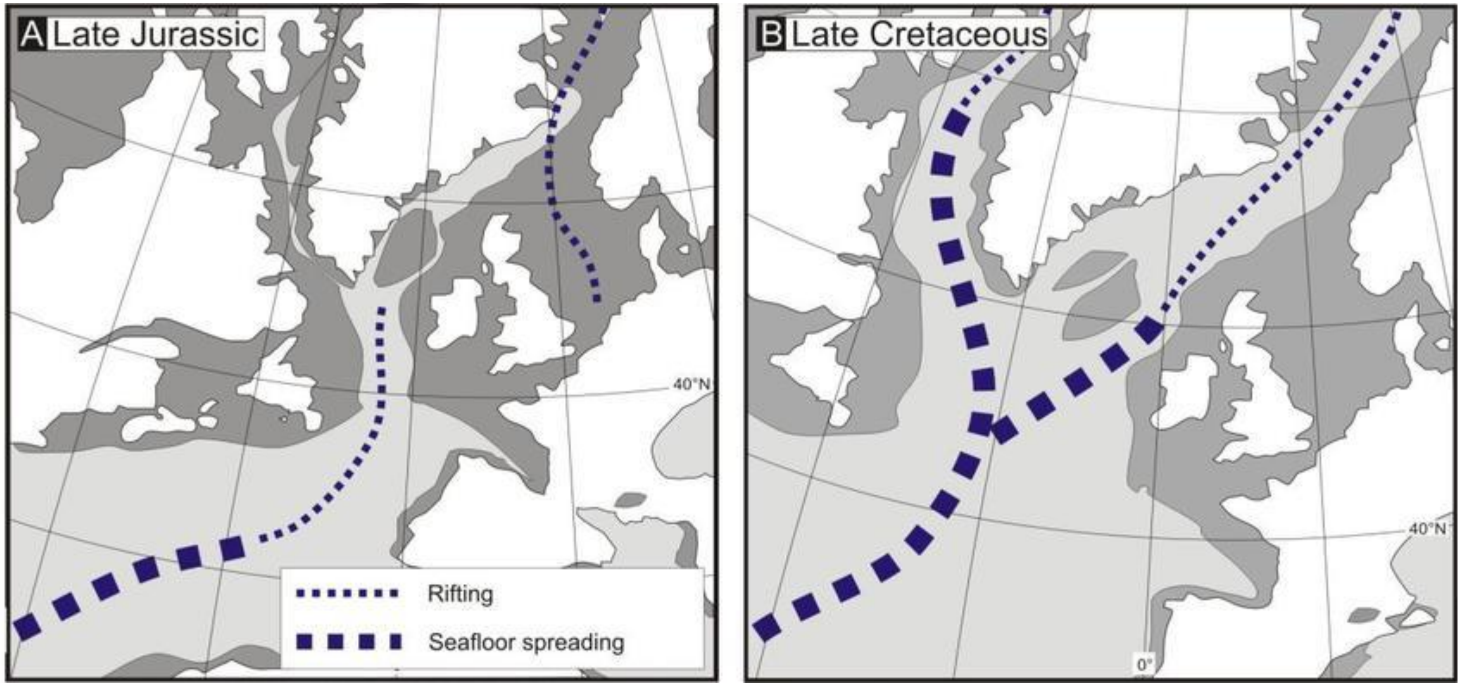


Figure 2.10: Schematic map showing propagating rifts and seafloor spreading in the Late Jurassic and Late Cretaceous respectively. From Doepke (2017)

2.4.2 Southern and Central North Atlantic Rift System Triassic-end of Mesozoic

The breakup of the North Atlantic involved multiple rift and breakup phases (Srivastava, 1978; Lundin, 2002; Oakey and Chalmers, 2012; Barnett-Moore et al., 2018; Gernigon et al., 2019). The rifting events that preceded the North Atlantic breakup, as evidenced by the stratigraphic and magmatic record, were multiphase. They began in the Permian, intensified and became more widespread during the Triassic—marked by several extensional 'pulses' from the Late Triassic to the Early Jurassic (Roberts et al., 1999; Brikiatis, 2016; Siedler et al., 2004; Alves and Cunha, 2018)—and persisted through the Jurassic, Cretaceous, and Cenozoic periods (Umpleby, 1979; Larsen et al., 2009; Stoker et al., 2016; Peace et al., 2018c). Following this prolonged, region-wide rifting, opening of the Atlantic was initiated in the Central Atlantic in the Jurassic and propagated into the proto-North Atlantic in Early Aptian time progressively opening the North Atlantic from south to north (e.g., Tucholke et al., 2007; Barnett-Moore et al., 2018).

Triassic passive rifting led to the emplacement of the central Atlantic magmatic province (200 Ma) LIP and the subsequent opening of the central Atlantic Ocean during the lowermost Jurassic (Lamotte et al., 2015). As seafloor spreading began in the Middle Jurassic, in the Central Atlantic, south of the Azores-Gibraltar Fracture Zone (AGFZ), the Southern North Atlantic rifting was facilitated by the northwards propagation of the rift axis from the Central Atlantic (Figure 2.10 & 2.11) into offshore Iberia and the Grand Banks of Canada prior to the complete establishment of seafloor spreading in the Early Cretaceous-Aptian (Peace et al., 2019). Many of the basins of the conjugate margins of the southern North Atlantic record this prolonged multi-phase, wide rifting history (Peace et al., 2019).

Continental rifting was initially driven by NW-SE extension between Newfoundland Iberia in the Late-Triassic-Early Jurassic (Gouiza et al., 2017). This is well recorded at outcrop in the Lusitanian Basin and in Southwest Iberia (Rasmussen et al., 1998). In the Lusitanian Basin, it is documented by the deposition of Triassic red fluvial clastics (Silves Formation) and Hettangian evaporites (Dagorda Formation) in fault-bounded basins (Sibuet and Ryan 1979; Alves et al., 2002). After the latest Triassic, regional subsidence prevailed in the Lusitanian Basin and promoted the widespread deposition of evaporites (Rasmussen et al., 1998). This early Jurassic rifting recorded in the Lusitanian Basin, West Iberia, offshore Nova Scotia and southern Newfoundland is associated with the event that led to the Central Atlantic Spreading (Roberts et al., 1999, Lundin 2002).

Rifting continued to propagate northwards between NW Newfoundland and Western Europe in the Middle Jurassic-Early Cretaceous (Tankard and Welsink, 1989). The main subsequent major phase of extension initiated in the Late Jurassic and continued through the Early Cretaceous, progressively opening the North Atlantic from south to north into the Bay of Biscay. The northward propagation of the Atlantic rift from Biscay into the Rockall Trough and Faeroe–Shetland Basin–Møre Basin completed the linkage to the Arctic rift, possibly as early as the Late Jurassic and certainly by the Albian–Aptian Roberts., et al 1999). For example, in the Jeanne d'Arc basin rifting was initiated during late Callovian-Kimmeridgian, with the most intense phase of that rifting occurring from the late Kimmeridgian to the Valanginian. Productive marine mudstones were laid down in the Jeanne d'Arc and Porcupine basins, while lacustrine rocks were laid down in the Celtic Sea (Butterworth et al., 1999). Further intervals with source rocks were deposited in the Rockall Trough northwards into the Faroe-Shetland Basins, up to Norway (Roberts et al., 1999). The Jurassic extension affected the whole North Atlantic region, and deep intra-continental rift basins existed from the Rockall Trough to the SW Barents Sea, with a separate branch into the North Sea.

A third, slightly diachronous and shorter rifting episode in Iberia, spanning the Late Oxfordian-early Kimmeridgian, resulted in widespread fault-related subsidence and halokinesis in areas with thick Hettangian salt, resulting in the formation of a rifted continental margin with 40+ discrete sub basins in the deep offshore regions (Alves et al., 2009). This rifting event in the Lusitanian Basin has been considered as a precursor event leading to the ocean spreading in the Tagus Abyssal Plain near the Jurassic-Cretaceous boundary (Wilson et al., 1989).

In the southern North Atlantic, the onset of seafloor spreading is interpreted at latest Jurassic-earliest Cretaceous in southwest Iberia, the Tagus Abyssal Plain (Late Tithonian; Strivastava et al., 2000; Merino et al., 2021). This phase correlates with rifting and continental breakup in the Grand Banks, Canada, which is recorded as Early Cretaceous in age. Breakup sequences in Iberia show that the rift propagated northwards (Alves and Cunha, 2018) towards the Galicia margin where breakup is recorded at Aptian-Albian level (Pereira and Alves, 2012; Eddy et al., 2017). This meaning that the break-up unconformity in Iberia is earliest Cretaceous in Southwest Iberia and marks a major geodynamic change in the evolution of the north Atlantic as the Grand Banks separated form Iberia, and the Flemish Cap from the Galicia Bank a few million years later (Tucholke et al. 2007; Gouiza et al., 2016).

In Northwest Iberia, Aptian-Albian times record a change from a tectono-sedimentary regime dominated by continental rifting to an oceanic and transgressive regime over the entire north Atlantic area. A change in type of extension was crucial to the North Atlantic domain; it documented the abandonment of the Jurassic rift arm that extended into the North Sea. Rifting was instead focussed in a chain of basins starting from the Iberia-Newfoundland Margins, via the Rockall-Hatton Trough, Faroe-Shetland, Møre, Vøring, Lofoten and Harstad Basins, and north into the Barents Sea. A separate arm also extended into the Labrador Sea, later separating Greenland from North America, which underwent NE-SW oriented extension.

The North Sea transitioned into stable epi-continental subsidence and the southern Atlantic rift achieved crustal separation in some places. At this time, uniform red calcareous claystones of the Rodby Formation were deposited over much of the North Sea as a result of a transgression triggered by the progradation of the spreading in the Atlantic northwards (Hesjedal and Hamar 1982). This rifting episode was responsible for the final scattering of the Pangea continents, opening the South Atlantic, and propagating into the Bay of Biscay via the Azores fracture zone during the Valanginian to early Hauterivian, and into the southern North Atlantic located between the Iberia-Newfoundland conjugate margins (NE Newfoundland and Goban Spur) (Lamotte et al., 2015; Srivastava et al., 1988).

In the Late Aptian times oceanic crust had formed in the SE Labrador Sea and NW Bay of Biscay. By the Late Cretaceous northwards propagating of the rift arm extended between Labrador and Greenland, recording the opening of the Labrador Sea (Dickie et al., 2011).

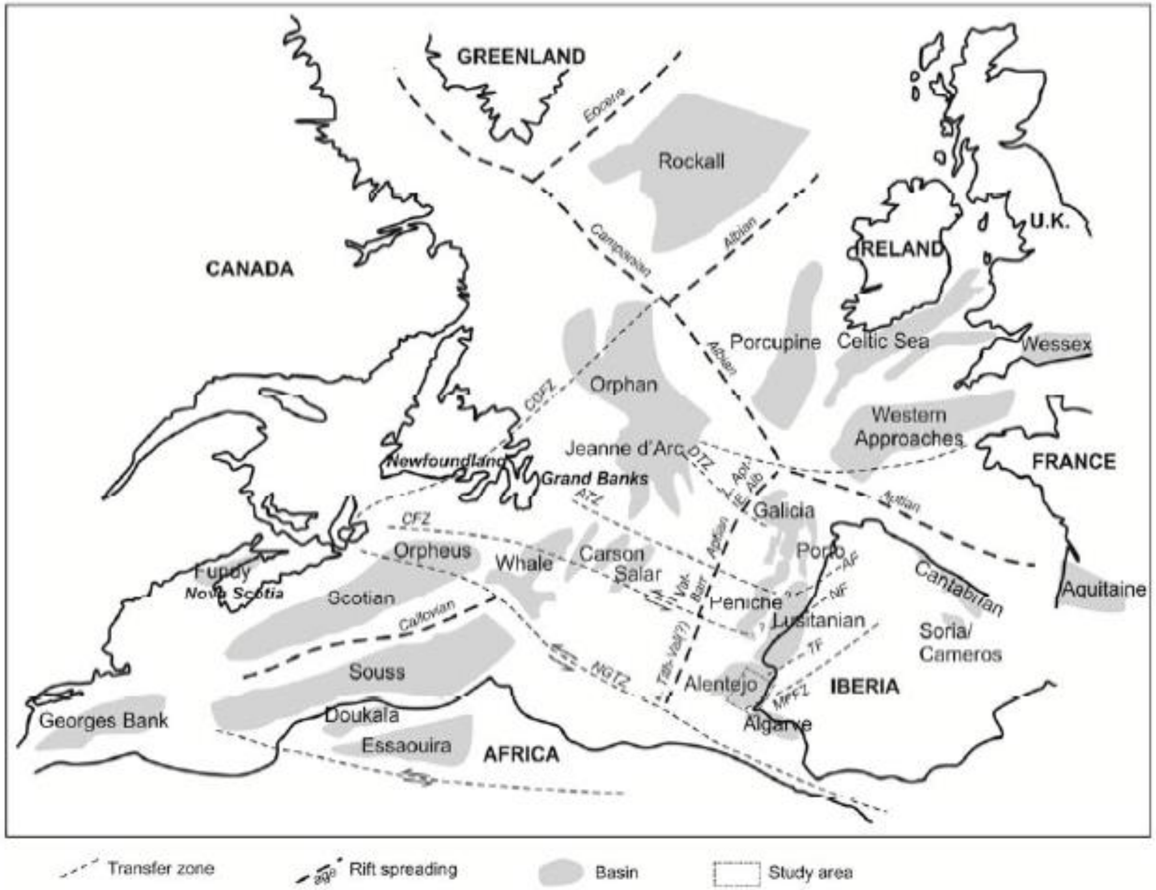


Figure 2.11: Palaeogeographic reconstruction of the North Atlantic during initial rifting stages (Late Triassic to Early Jurassic) with associated ages of seafloor spreading from Hiscott et al. (1990) highlighting northwards propagating rifts and main Mesozoic rift basins (based on Hiscott et al., 1990). NGTZ- Newfoundland-Gibraltar Transfer Zone, MPFZ- Messejana-Plasencia Fault Zone, NF – Nazaré Fault, TF – Tagus Fault, AF- Aveiro Fault, CFZ- Collector Fault Zone, ATZ- Avalon Transfer zone, DTZ- Dominion Transfer Zone, CGFZ- Charlie Gibbs Fracture Zone. Figure modified from Pereira (2013).

2.4.3 Rifting in the North Sea and Northeast Atlantic area

The North Sea experienced rifting over the Mesozoic and represents a failed arm of the Arctic-North Atlantic rift system. Rifting intensified through the Middle Jurassic to earliest Cretaceous and strain migration during multiphase extension in the northern North Sea was influenced by flexural bending associated with postrift thermal subsidence and far-field stresses from rifting in the North Atlantic (Bell et al., 2014) and led to the movement of the locus of extension west of the United Kingdom to future plate separation (Ziegler, 1991) resulting in the failed North Sea rift.

According to many authors, the Triassic was characterised as differential subsidence of basins and heavy sediment accumulation, coupled with marine incursion episodes in the Northeast Atlantic area as well as the North Sea Basins. However, no real marine connection between realms was established at this time (Doré, 1991; 1992; Roberts et al., 1999). During the earliest Triassic this rift system propagated into the North Sea area where the Viking and Central Grabens, The Horda-Egersund half-graben and The Moray Firth-Witch Ground graben system began to subside (Ziegler, 1991) cross cutting the previous Permian basins in the North Sea area. The early Triassic also saw marine incursions into the southern North Sea via the Tethyan shelves, with transgressions reaching the Egersund Basin in the Middle Triassic (Ziegler, 1991). The Middle to Late Triassic was, therefore, characterised by marine ingressions from the boreal realm into the Northern North Atlantic region and from the Tethyan realm into the North Sea Area region (Doré, 1991).

In the Northeast Atlantic area, as rifting propagated and transgressive marine pulses continued into the Early Jurassic, seawater inundated basins primarily due to differential subsidence between grabens, allowing a seaway to be formed over previous sites of continental continuity. Seawater incursions followed rift propagation northwards from what is now the Bay of Biscay in Northern Iberia into the Rockall Trough, into the Faeroe-Shetland Basin and into a part of the rift arm beginning to separate Greenland and Norway, forming a connection for the first time between the low-palaeolatitude Tethys Ocean realm and the high-palaeolatitude Boreal (Arctic) realm by, at latest, Toarcian times (Brikiatis, 2016; Ziegler, 1982, Doré, 1991; Roberts et al., 1999). This seaway providing the connection between North and South has been called the *Laurasian Seaway* (Figure 2.12).

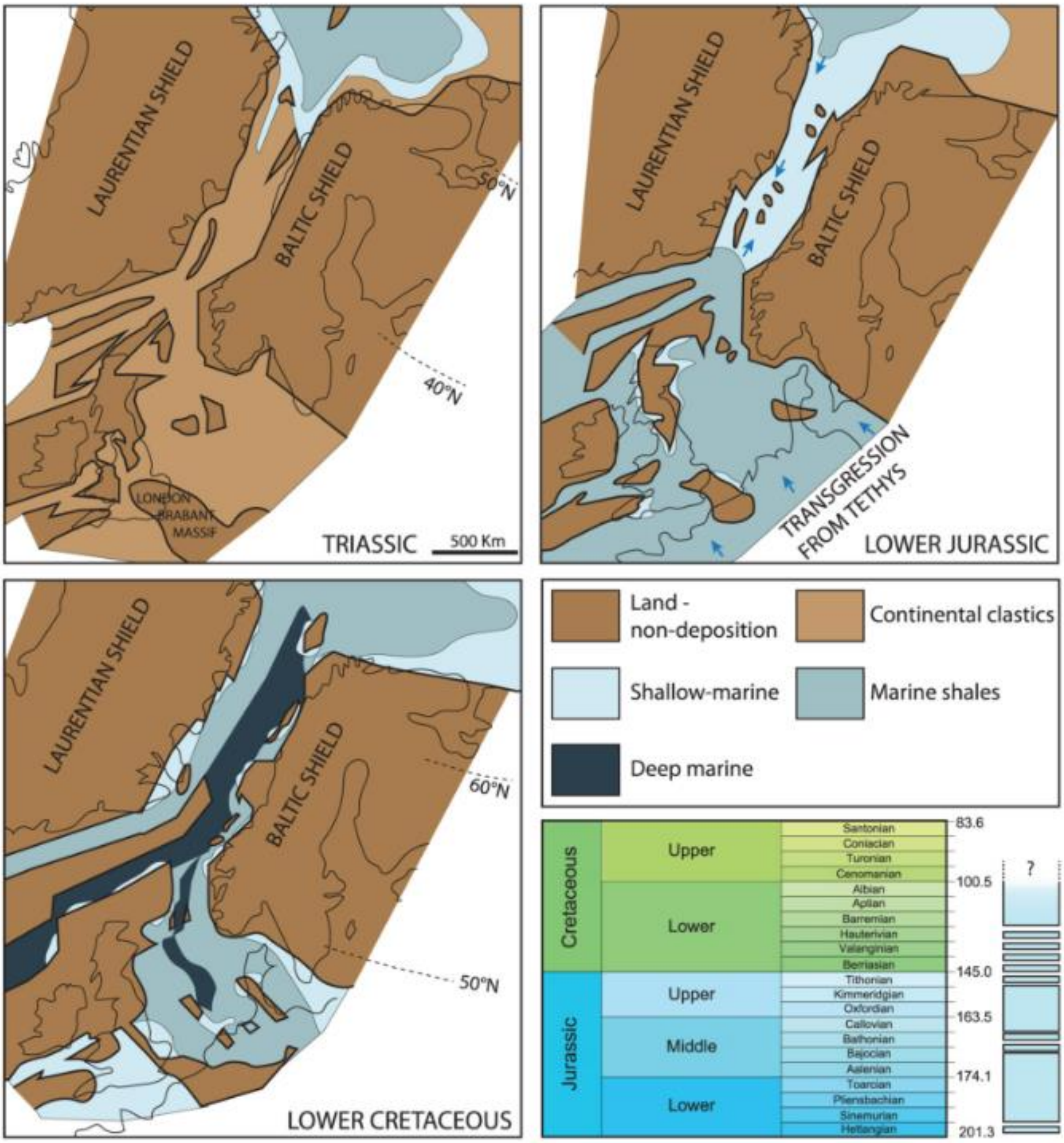


Figure 2.12: Evolution of the Laurasian Seaway from the Triassic to the Lower Createcous (palaeolatitudes are indicated) From Rossi et al., 2023, redrawn from Doré, 1991. Highlighting the connection between the equatorial Tethys and the Boreal realms via the Laurasian Seaway.

A Sinemurian-Pliensbachian transgression resulted in the deposition of the marine Dunlin Formation in the North Sea, with sandy accumulations still occurring on the margins of basins in the form of the Cook and Johansen formations (Figure 2.13). This same Sinemurian-Pliensbachian transgression brought full marine conditions to the NE Atlantic system between Norway and Greenland, with tide-dominated sand deposition. Palaeontological research by Dera et al. (2011) suggests that ammonite populations in the Sinemurian provide evidence that the Laurasian Seaway (also called Viking Corridor) was a passage between realms, where water exchanges occurred continuously, but the magnitude of such exchanges were controlled by fluctuations in sea level and currents. A late Pliensbachian low sea level temporarily segregated populations until full recovery in the Toarcian, an event culminating in the deposition of Toarcian shales and the establishment of a seaway. The likely reason behind the unsuccessful connection between realms, recorded until the Toarcian, was due to sediment deposition keeping pace with the development of accommodation space and rising sea levels throughout the Triassic. Consequently, a relative lack of true marine strata is observed until the Jurassic (Skjerven et al., 1983).

Palaeogeographic reconstructions of the North Atlantic Area show that from, at least, the Early Jurassic and through the rest of the Mesozoic, a combination of shallow and deeper marine basins and channels existed connecting the Tethys region and the Arctic via the North Atlantic rift system (Ziegler, 1982, Doré; 1991; Roberts et al., 1999). This is supported by Ziegler (1991), that characterises the North Sea rift system as continuing to subside through the Early Jurassic with little volcanic activity.

In the Middle Jurassic, the connection of the two realms ceased due to major thermal uplift in the Central North Sea area (Doré, 1991). The regional uplift, as documented by Underhill and Partington (1993), occurred over what is now the trilete area of the North Sea between the Moray Firth, Viking and Central Graben systems. Stratigraphic correlations of units on the periphery of the dome have shown that the unconformity marking such a regional uplift is Aalenian in age (Underhill and Partington, 1993). Below mid-Jurassic strata in the North Sea, this unconformity has a northerly limit of 59 degrees and spans Scotland, central England and down into Denmark (Ziegler, 1992).

The distribution of the Lower and Middle Jurassic rocks in the North Sea is therefore complex. They are often found truncated underneath unconformable Upper Jurassic and Cretaceous strata separated by the intra-Aalenian unconformity (Underhill and Partington, 1993). Late Jurassic rifting and erosion is accountable for the confinement of lower-middle Jurassic strata near hanging-walls of Late Jurassic faults, for example in the western limit of the south Viking Graben and the east limit of inner Moray Firth. The North Sea dome itself has been described as a stratigraphic sub-aerial eroded dome in the central North Sea region that was 1000 km across, having later subsided due to Mid- Jurassic rifting (Underhill and Partington, 1993) and replaced by the trilete system (Ziegler 1992). Structural analysis of isopach maps in the area, however, does show that the Jurassic rift system in the Viking-Central Graben may have continued into the Cretaceous and that the dome at this time was not emergent as sea level was high and, consequently, no erosion took place (Graversen, 2005).

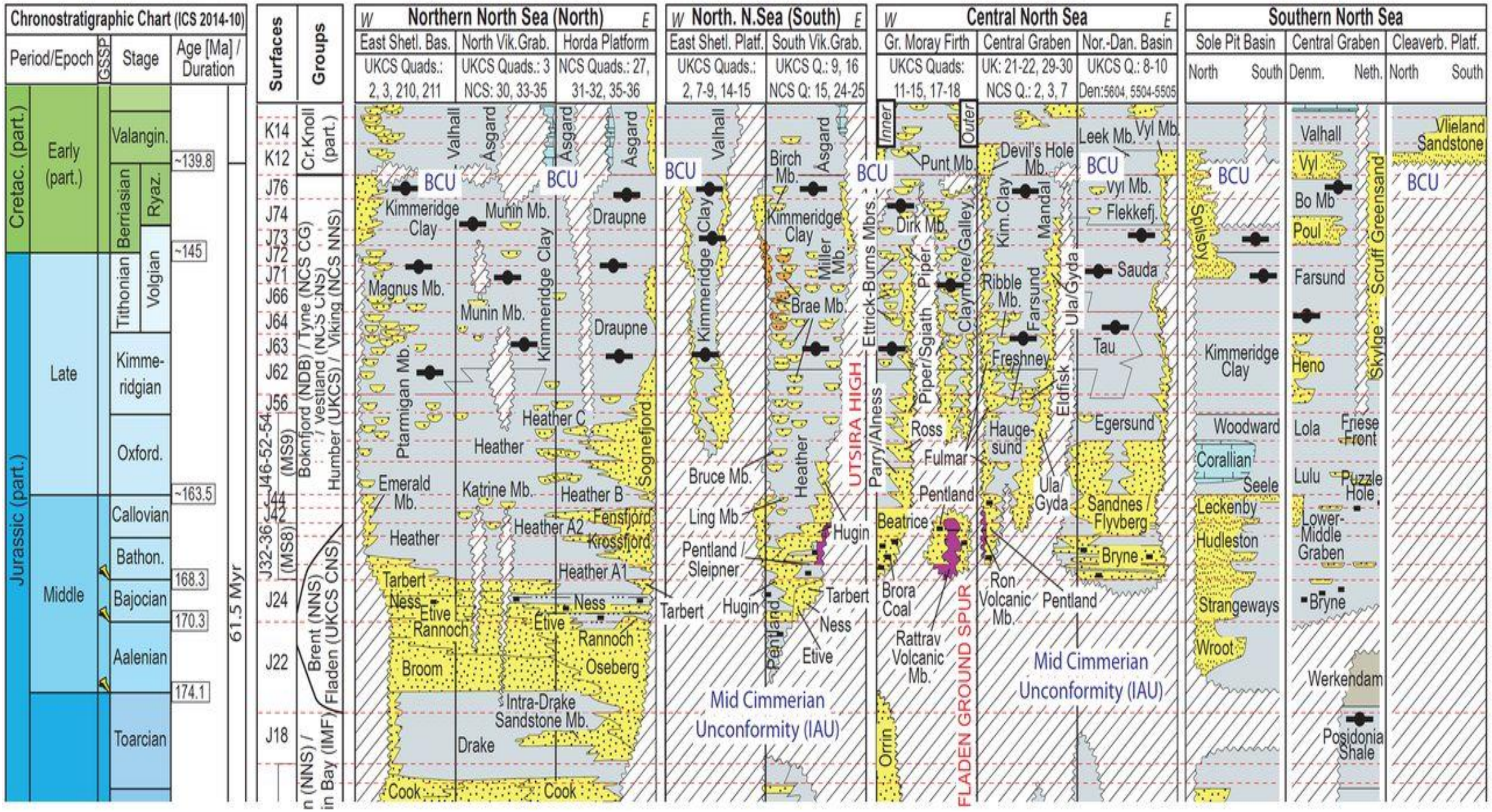


Figure 2.13: Cross border stratigraphy from late Early Jurassic to the Early Cretaceous, highlighting correlative stratigraphic formations, diachoronous units and differences in nomenclature between the UKCS and NCS, as well as the North Sea Dome Unconformity (Mid-Cimmerian or IAU) and the Base Cetaceous Unconformity. From Patruno et al., 2022 .

Uplift of the dome also stifled a chiefly marine transgressive regime in the Middle Jurassic, suspending marine conditions in the northern North Sea with accompanying basin flank uplift and sea level fall (Ziegler 1982). Subsequent erosion of the dome and uplifted basin flanks led to increased sediment supply for the prograding lower Brent deltaic system into the proto-Viking Graben during Aelanian-Bajocian (Fjellanger et al., 1996). depositing the upper Brent deltaic succession related to a Late Bajocian-early Bathonian transgression on the Norwegian shelf. The Rannoch, Etive, Ness and Tarbert formations of the Brent Group, (Figure 2.13), formed from the early Bajocian to Bathonian therefore record a full upper and lower delta complex (Johannesson et al., 1995).

Outside of the North Sea, in the Atlantic area, a Aalenian-Bajocian hiatus recorded in East Greenland was followed by late Bajocian transgression and deposition of the Pelion member, a marine sandstone unit (Doré, 1992). Rifting in East Greenland resumed between the Bajocian to Bathonian times in association with regional extension and sea-level transgression. Deep-water conditions in the Greenland-Norwegian area extended from the Møre Basin in the North West to the Rockall Trough in the South East in the Bathonian. Rift-flank uplift occurred in some basins during this time, with erosion affecting strata as old as the Permo-Triassic in the Faroe Basin (Chery et al., 1992).

The initiation and cessation of the rifting from the Middle-Late Jurassic in the North Sea was diachronous across the basin (Holgate et al., 2013) In the area of the Viking Graben rifting initiated in the Bajocian (Johannessen et al., 1995),with its establishment occurring at the expense of the Brent Delta as sea levels rose (Haq et al. 1987). Half-grabens near the axis of the Viking Graben record faulting at the end of the Middle Jurassic. This is the case of the Oseburg and Brage fault blocks, which show sediment wedges in the Bathonian and Callovian

Heather Formation that thicken downdip, a consequence of fault block rotation during their deposition (Mcleod and Underhill, 1999). Fault-block rotation in the North Sea was quite extensive at this time; Bajocian-Callovian units increase tenfold in thickness near major faults. Several of these rotated fault blocks became temporary islands in the area that is now the Viking Graben, leading to the erosion of older Jurassic strata on the fault block highs (Mcleod and Underhill, 1999). The connection between the Boreal and Tethyan realms is suggested to have been re-established in the Callovian, according to marine faunal evidence, due to subsidence of the North Sea dome (Calloman, 1984; Calloman 2003; Doré, 1991, Brikiatis, 2016).

Multiple phases of faulting in the North Sea occurred at the end of the Middle Jurassic, followed by major rifting episodes in the Late Jurassic. The Brent Group's east-west trending facies belt that developed in the Bathonian was, by the Cretaceous, rearranged into a series of north-trending fault blocks. Faulting in the Jurassic locally overcame the effects of sea-level rise and transgression, creating local topography within discrete basins. Those basins with pronounced footwall highs supplied sediment to their neighbouring basins, whereas those basins with less pronounced footwall uplift were eventually starved of sediment (Ravnas et al., 2000).

The Late Jurassic is responsible for 80% of the discovered reserves along the North Atlantic margin, including the North Sea, in both syn-rift and pre-rift reservoirs (Knott et al., 1993). The Late Jurassic saw a continuation of a chiefly marine transgressive regime (Doré, 1991). The Late Jurassic succession in the North Sea includes the Humber Group (UK) and its equivalent, the Viking Group in the Norwegian sector. Belonging to these stratigraphic groups are several notable diachronous mudstone formations - the Heather, Kimmeridge clay and Draupne formations, the Fulmar and Piper shallow marine sandstones, the deep marine Magnus sandstone member and the coastal deltaic Sognejford and Fensjford formations (Figure 2.13). Similar facies associations can be seen further north in the NE Atlantic region to the Barents Sea (Doré, 1991).

The Oxfordian-Kimmeridgian recorded further subsidence over the entire North Atlantic area, and true marine black shales were deposited. The widespread marine shales of the Heather and Draupne formations recorded this change in the North Sea (Figures 2.13). By the early Oxfordian, the South Viking Graben was completely inundated and marine mudstone deposition predominated there. Restricted marine water circulation occurred due to a highly variable and fragmented basin-floor bathymetry, with the hanging-wall of the rift axes a scale of several hundred metres (Miller, 1990).

The combination of the complex Late Jurassic tectonic activity and the latest Jurassic-earliest Cretaceous (Volgian-Tithonian) sea-level fall in the North Sea gave way to temporary closure of marine connection Europe (Roberts et al., 1999). A latest Kimmeridgian sea-level fall was also documented around Iberia (Alves et al., 2009). The reactivation of the central North Sea High likely acted as land barrier in the earliest Cretaceous and, consequently, the provinciality of ammonite faunas was at its highest in the Berriasian (Brikiatis, 2016). Evidence of emergence at this time comes in the form of the paralic Wealden deposits in southern England (Berriasian to Barremian) and the deltaic rocks in Norway and Greenland (Doré, 1992). Subsequently, a late Berriasian transgression re-established faunal connections (Rawson and Riley, 1982) via the establishment of a more complex Cretaceous seaway.

From the Berriasian to Barremian, marine shale deposition occurred in the North Sea within the Asgard and Valhall formations (Figure 2.13). In the earliest Cretaceous, a north-east trending rift extended from the Vøring Basin south to the Bay of Biscay, and somewhat replaced the North Sea and Arctic rift where activity stopped (Coward et al. 2003; Brikiatis, 2016).

In the literature, the limits of Lower Cretaceous strata are taken at the base and the top of the Cromer Knoll Group in the North Sea. The facies change at the base of the Cromer Knoll Group is marked by an upward change from the dark shales and organic rich claystones of the Kimmeridge clay and its equivalents deposited in anoxic conditions to light-coloured argillaceous marine sediments with a varying content of calcareous material. This change is essentially synchronous across the North Sea and dated as latest Ryazanian, reflecting a rapid turnover of water mass, and oxygenation, in the epi-continental seaway as described by Rawson and Riley (1982). This change is marked by a regional unconformity that is commonly referred to as the Base Cretaceous Unconformity, or BCU (Figure 2.13).

The Base Cretaceous Unconformity - previously named in the literature as Cimmerian unconformity or North Sea Unconformity - was established in the North Sea as a result of the deposition of transgressive sediments over the syn-rift succession undergoing passive thermal subsidence due to the abandonment of the Jurassic rift arm that extended into the North Sea, and subsequent cessation of rifting in the area. These transgressive sediments are attributed to the late Berriasian transgression (Brown and Fisher, 1977) and show a marked facies change and a distinct systems tract (Kyrkjebo et al., 2004). Lower Cretaceous stratigraphy shows competition of the effect of topographic relief inherited from latest Jurassic rift on accommodation space, and also of post-thermal collapse and long term changes in global sea level, all overprinted by local halokinetic and tectonic-eustatic events.

2.5 Rationale and Aims of this research

2.5.1 Rationale

The Mesozoic witnessed profound tectonic transformations that have been pivotal in shaping the present-day geology of the North Atlantic.

This PhD thesis aims to elucidate the intricate interplay between tectonic, sedimentary, and geochemical processes during the Triassic-Early Jurassic continental rifting in the North Atlantic. By leveraging reprocessed seismic data and comprehensive well analyses in Western Iberia, it seeks to unravel the complex subsidence history and the genesis of the South Laurasian Seaway, a critical juncture in the geological evolution of the area. In the North Sea, analysis of an extensive geochemical dataset seeks to shed light on the organic-rich sediments that may hold clues to the region's rifting history.

The inclusion of both regions is an approach to understanding the broader implications of rifting over the North Atlantic during this time. This thesis argues that the understanding of Mesozoic ocean seaways and their associated strata can be significantly enhanced by acknowledging the dynamic interplay between tectonics, stratigraphy and organic matter supply during these early rifting stages. The juxtaposition of two distinct regions within the North Atlantic provides a unique lens through which the broader implications of rifting can be discerned.

In acknowledging the limitations of the current methodologies and the datasets utilised, the thesis underscores the potential for future research. The findings establish a foundational understanding for further exploration, suggesting the potential for discovering richer geological insights.

2.5.2 Aims

The work assesses the Triassic through to Cretaceous evolution of the North Atlantic Ocean with focus on the existence of several proto-oceanic seaways, their location, geometry, time of inception and duration. The use of regional, high-quality 2D and well data allowed a thorough investigation into basins offshore West Iberia in terms of their structural and stratigraphic evolution. This was important to critically assess the sequence stratigraphic record of the Mesozoic rifting events, with emphasis on the earliest Mesozoic successions. Additionally, it endeavours to characterise the geochemical signatures of Upper Jurassic source rocks within the broader context of these geotectonic features. In essence, the objectives of this thesis are as follows:

1. **Palaeo-seaway Development**: To map the extent and configuration of the South Laurasian Seaway in West Iberia , characterising its segmentation and subsidence.

2. **Depositional Patterns**: To compare depositional stacking patterns across West Iberia and Northwest Europe, seeking commonalities that could suggest a coherent regional geological evolution.

3. **Geochemical Characterisation**: To understand the geochemical characteristics of Upper Jurassic source rocks in the context of the North Atlantic, analysing kerogen types and biomarkers as proxies for terrestrial versus marine organic contributions during deposition, with an aim to understand the changing organic inputs during rift progression.

4. **Future Research Directions**: To recommend avenues for future investigations that can build on the findings of this research, potentially focusing on the detailed mapping of geochemical signatures and their relation to evolving paleoenvironmental conditions.

The culmination of these aims will contribute to a more nuanced understanding of the geological processes that shaped the North Atlantic during a formative period of Earth's history. The insights gleaned from this study will have broader implications for regional geology, palaeoceanography, and hydrocarbon exploration.

The work presented in this thesis is conducted as part of the NERC Centre for Doctoral Training (CDT) Oil and Gas UK. The objectives of this thesis relate to exploration of challenging offshore environments, and recognising new prospects (conventional and unconventional) along North Atlantic margins.

3 Significance of Upper Triassic to Lower Jurassic salt in the identification of palaeo-seaways in the North Atlantic

3.1 Abstract

This work uses high-quality reprocessed 2D data, tied to borehole information, to address the development of North Atlantic Jurassic seaways on the continental margin of West Iberia. The seismic data reveal the full thickness of Mesozoic syn-rift strata filling deep-offshore basins in this latter region. Tectonic subsidence resulted in the separation of the seaway into distal and proximal sectors. As a result, backstripped curves for the Early Jurassic depocentres in West Iberia document important tectonic subsidence during the Late Triassic-earliest Jurassic. The Lusitanian and Peniche basins were part of the same seaway during the early stages of rifting, with important rift-shoulder exhumation occurring between the seaway and the distal margin from Late Jurassic onwards. We estimate 5 km subsidence in the deep-offshore Peniche Basin during the Late Triassic-Early Jurassic when compared to the ~1.1 km recorded in the proximal Lusitanian Basin. Critically, borehole stratigraphy shows that early Mesozoic basins in West Iberia, Newfoundland, and the North Sea show a tripartite depositional evolution of stacked continental, evaporitic, and marine strata. The similar Early Triassic-Jurassic seismic and stratigraphic records of the Lusitanian and Peniche basins suggest a co-genetic evolution with other early Mesozoic basins along the North Atlantic margin.

3.2 Geological Setting of West Iberia

3.2.1 Physiography

The continental shelf between the city of Porto (∼41°N) and the Nazaré Fault is associated with the Iberia Abyssal Plain (Figure 3.1a). In this area, the shelf is narrow (~ 60 km wide), showing a steep bathymetric drop into basins created by a slope fault system separating relatively deeper continental-slope basins from the Lusitanian Basin (Alves and Cunha, 2018). The central and northern areas of the West Iberian margin are dissected by first order transfer faults associated with modern submarine canyon systems that reach the abyssal plain (Figure 1a). From north to south, the main basins of the entire West Iberian margin are the Galicia, Porto, Peniche, Lusitanian and Alentejo basins (Pinheiro et al., 1996). West Iberia has been described to contain more than 40 sub-basins in its deep-offshore areas (Alves et al., 2009).

The Lusitanian Basin comprises a Mesozoic rift basin extending 250 km in a roughly north-south direction, and 100 km east-west. The basin comprises the proximal part of West Iberia's continental margin (Figure 3.1b). In contrast, the Peniche Basin is a 300 km long north-south trending deep-water trough divided into outer proximal and a distal segments, which extend westwards into the Iberia Abyssal Plain for several hundreds of kilometres (Alves et al., 2006). There is little direct stratigraphic information on the Peniche Basin due to absence of borehole data in the largest depocentres in this area. Information on the sedimentary infill derives from seismic stratigraphic analyses tied to more than 50 exploration wells on the shelf, DSDP/ODP Data, and correlations with outcrop analogues (Alves et al., 2006).

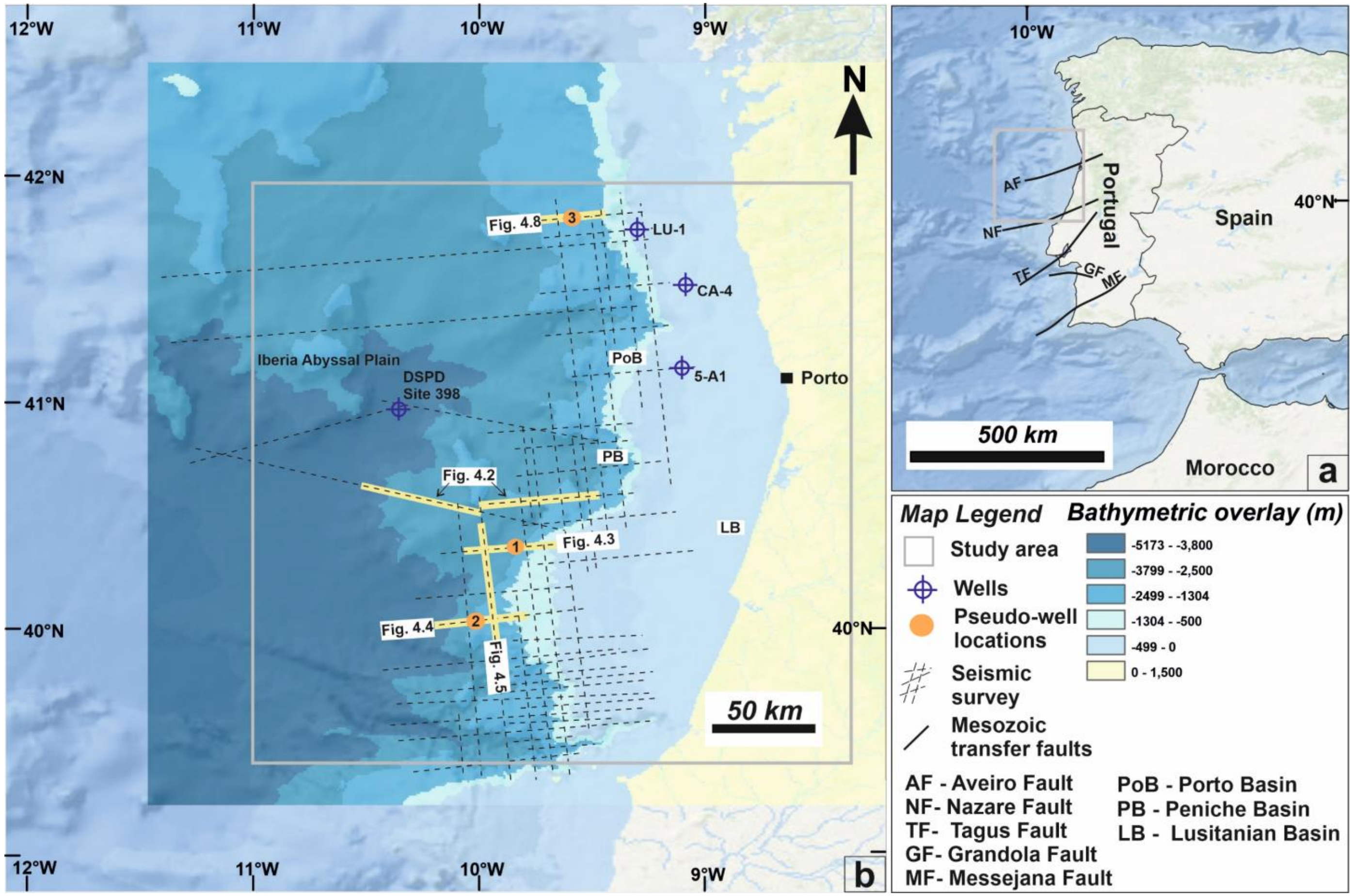


Figure 3.1: a) Map of the West Iberian margin and geographical location showing major transfer faults and the study area. b) Bathymetric map of study area depicting interpreted seismic grid with location of offshore industry and DSDP wells (Esri GEBCO 2019).

3.2.2 Syn-rift evolution and continental breakup

The Mesozoic evolution of West Iberia was dominated by four distinct rift episodes: Triassic (Rift 1), Sinemurian–early Pliensbachian (Rift 2), and late Oxfordian (Rift 3). Rift 4 occurred in the latest Jurassic–Early Cretaceous and is chiefly recorded in the Peniche and Porto basins (Wilson et al., 1989; Wilson, Manatschal and Wise, 2001; Alves et al., 2009) (Figure 3.2).

The Triassic rift phase (Rift 1) is well recorded at outcrop in the Lusitanian Basin and in Southwest Iberia (Rasmussen et al., 1998). It was associated with the first Mesozoic extensional phases that affected the Eurasian-American domain from the Permian to the late Early Jurassic (Arthaud and Matte, 1977). In the Lusitanian Basin it documented by the deposition of Triassic red fluvial clastics (Silves Formation) and Hettangian evaporites (Dagorda Formation) in fault-bounded basins (Sibuet and Ryan 1979; Alves et al., 2002). After the latest Triassic, regional subsidence prevailed in the Lusitanian Basin to promote the widespread deposition of evaporites (Rasmussen et al., 1998) (Figure 3.2).

The Sinemurian to Pliensbachian Rift 2 was best developed south of the Nazaré Fault, where marine deposition first occurred (Stapel et al., 1996). After Rift 2, Lower and Middle Jurassic carbonate and mudstone reflects a northwest-dipping carbonate ramp developed in a regional setting dominated by slow, widespread subsidence well before continental breakup was achieved (Coimbra and Brenha formations; Toarcian–Late Callovian (Wilson et al., 1989; Pereira and Alves, 2012).

The late Oxfordian Rift 3 is associated with rifting and subsequent continental breakup of the region where Tagus Abyssal Plain is located (Alves et al., 2009). This phase manifested itself in the Lusitanian Basin where several sub-basins developed. Two distinct depositional episodes are recorded in this basin: a) a first episode dominated by widespread carbonate deposition from the Early to Late Oxfordian (Cabo Mondego and Montejunto formations), b) a second episode documenting a large influx of clastic material during the Kimmeridgian (Abadia Formation; Wilson et al., 1989).

The fourth rift episode (Rift 4) occurred in the Early Cretaceous in association with the migration of the rift axis from the Tagus Abyssal Plain to the Iberian Abyssal Plain (Alves and Cunha, 2018). It was recorded in the continental slope basins west of the Lusitanian Basin, Porto Basin and in the zone of transitional crust drilled by ODP legs 149 and 173. This rifting episode generated a new rift trough and evidence exists that the Nazaré fault separated Berriasian–early Aptian seafloor spreading at the Tagus Abyssal Plain from a region still experiencing continental rifting northwards to the Charlie-Gibbs Fracture Zone, until the late Aptian-early Albian (Driscoll et al., 1995; Dean et al., 2015).

Continental breakup was diachronous across the North Atlantic (Pinheiro et al., 1996; Srivastava et al., 1990; Boillot, 1989; Stapel et al., 1996). A breakup sequence in the deep-water basins west of Peniche, defined by Soares et al. (2012), marks the period from the onset of continental breakup to the establishment of thermal relaxation on a fully rifted margin; it was dated as spanning the late Aptian to Turonian. In southwest Iberia, the breakup sequence developed from the Berriasian to the Barremian (Alves and Cunha, 2018). On the Newfoundland margin, several of these sequences are documented on the Atlantic Margin of Canada as continental breakup propagated northwards into the Labrador Sea (Alves and Cunha, 2018).

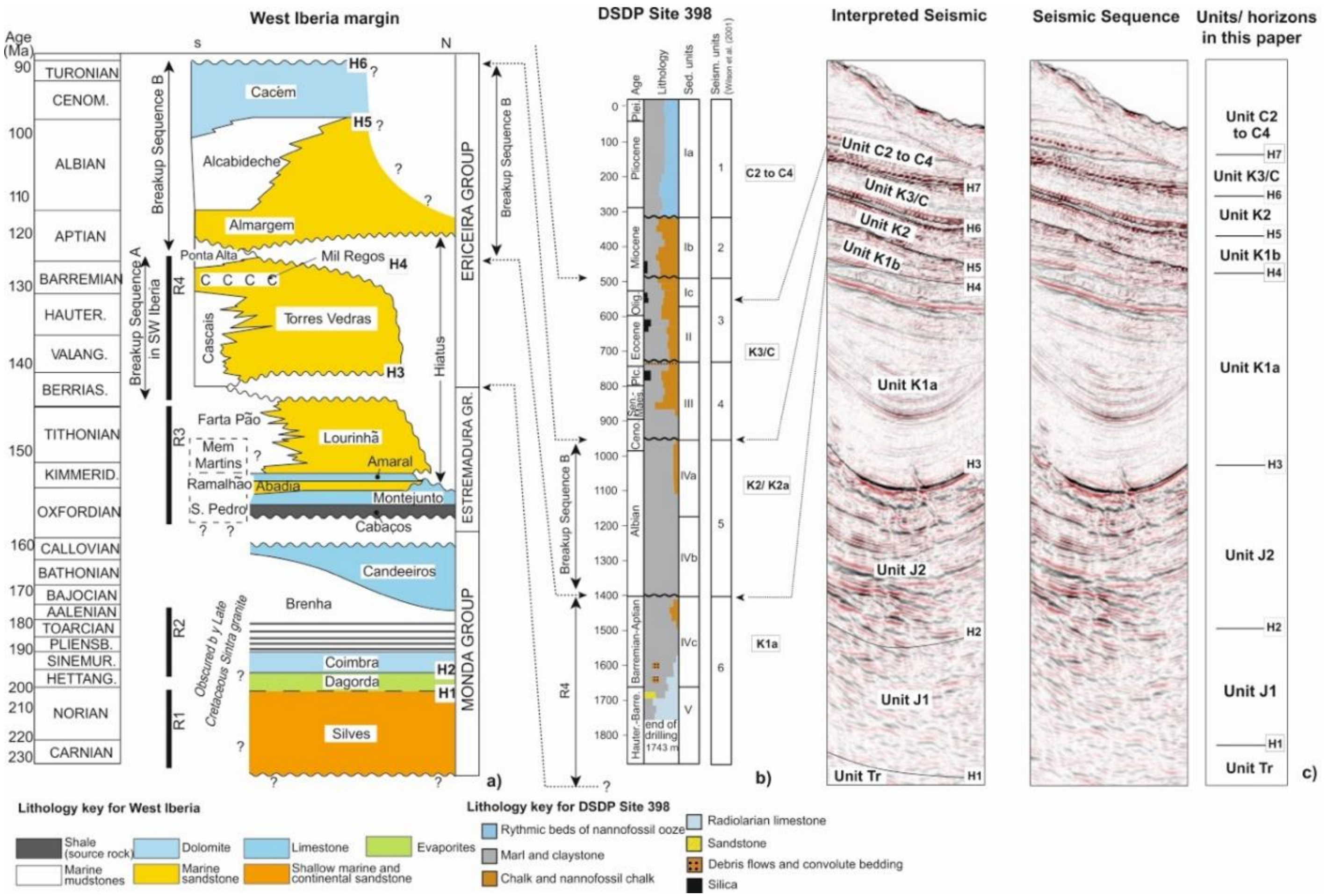


Figure 3.2: Correlation panel between interpreted seismic stratigraphic units and well data from the West Iberian Margin (Alves and Cunha, 2018) and DSDP Site 398 (Groupe Galice, 1979; Rehault and Mauffret, 1979). See Figures 3.1b and 3.7 for detailed location of the seismic section and DSDP Site 398. Interpreted seismic horizons (Hn) are overlain on the assumed West Iberian margin equivalents.

3.3 Introduction

Extensive seaways can form during continental rifting, providing a marine passage between two or more pre-existing oceans (Korte et al., 2015). They also establish conduits of marine heat along newly developed continental margins, influencing regional climate, and are repeatedly documented in the geological record (Berggren, 1982; Lear, Rosenthal and Wright, 2003; Smith and Pickering, 2003; Sijp et al., 2014). As one of the examples best documented in the literature, the Equatorial Atlantic Gateway developed first in the late Early Cretaceous to form a connection between the Central and South domains of the Atlantic Ocean (Bengtson et al. 2007). The Hispanic Corridor is another such seaway developed in the Early Jurassic, and provided a connection between the Palaeo-Pacific and the western Tethys Ocean. This corridor was likely established between North America, South America and Africa as early as the Hettangian based on the analysis of mixed bivalve fossil populations occurring in these three continents (Sha, 2002). It is one of the few Jurassic seaways described in the literature that is clearly associated with the breakup of the supercontinent Pangea. Younger seaways include: 1) the Red Sea, which has provided a connection between the Indian and the Atlantic Ocean via the Mediterranean Sea since the Late Paleogene (Gerges, 2002), and 2) the Arctic Gateway, which forms a connection between the Pacific and the Arctic Ocean since, at least, the Late Miocene (Marincovich and Gladenkov, 1999; Woodgate and Aagaard, 2005).

During the Early Jurassic, Northwest Europe and the North Atlantic as a whole recorded the development of a series of ocean seaways between the Western Tethyan realm in the south and the Boreal realm in the north (Ziegler, 1975). The Laurasian Seaway is the collective term to describe the interconnected seaways and straits that existed in the North Sea and North Atlantic area during the Early Jurassic (Bjerrum et al., 2001). The same system is alternatively referred to as the European Epicontinental Seaway in some publications (e.g. Harazim et al., 2013). The Viking Corridor, one marine connection identified largely from palaeobiogeographic research, was established in the Early Jurassic between Greenland, Norway, and the Northern part of the North Sea (Callomon, 2003; Korte et al., 2015). It provided the final connection to the Arctic domain from a northwards propagating rift system, with marine water spilling in from the Faroe-Shetland, Møre, and Vøring basins (Doré, 1991; Brikiatis, 2016). However, further south into what are now Iberia and the Bay of Biscay, relatively little is known about the palaeogeographic and palaeobathymetric history of the Laurasian Seaway.

The improved resolution of reprocessed 2D seismic data provided by TGS allowed us, for the first time, to interpret the base of latest Triassic – earliest Jurassic salt units to reveal a large offshore salt unit along West Iberia (Figure 3.1). Detailed interpretation of syn-rift strata and tectonic subsidence curves for the Lusitanian, Porto and Peniche basins, are used in this work to understand the palaeo-position and width of this Triassic-Early Jurassic seaway (Figure 3.1a and b). In summary, this chapter aims to address the following research questions:

1) What was the geometry and subsidence history of early rift basins in a segment of the North Atlantic supported by borehole and stratigraphic data?

2) What is the extent and the geometry of the south Laurasian Seaway offshore West Iberia?

3) Is there a commonality in the pattern of sedimentary deposits in the seaway, and is this similar to other seaways in Northwest Europe?

It is important to stress that the earliest Jurassic evaporite successions in West Iberia relate to an episode of crustal stretching during continental rifting. Syn-stretching salt is one division of the classification of passive margin salt basins defined by Rowan (2014); this salt is commonly deposited during active continental rifting. Early deposition of this type means that the salt deposit is restricted to proximal portions of the conjugate margin pair (Rowan, 2014). Syn-stretching salt is deposited directly in active half-grabens to mark the first incursion of marine water into the basins.

3.4 Chapter Specific Data and Methods

The interpreted seismic survey covers an area of 30,158 km^2 over the West Iberian Margin (Figure 3.1b). This dataset comprises 2D lines acquired by TGS in 1998, later reprocessed in TWTT to image the full extent of syn-rift basins offshore West Iberia. The interpreted seismic grid includes 2D multichannel two-way time domain data, acquired using 6000 m long streamers to a total of 66 navigation lines. The seismic data are stacked at a 4 ms sampling rate and displayed in zero-phase European SEG convention such that an increase in acoustic impedance with depth results in a red reflectivity peak, while a negative trough will be displayed in black. In this work, interpretation was completed to 9.0 s TWTT, compared to the ~7.0 s TWTT of older data (Figure 3.4) using Schlumberger's Petrel®. The new 2D data were also tied to exploration wells and DSDP/ODP data on Schlumberger's Petrel®.

Schlumberger's PetroMod® was used in this study to compute tectonic subsidence using 1-D Airy backstripping techniques (Watts and Ryan; Steckler and Watts, 1978). The software was used to investigate and contrast the burial history of strata in proximal and distal basins, and to generate subsidence curves to determine the timing of critical events. We analysed backstripping results for three (3) industry wells on the continental shelf and upper continental slope and built three (3) pseudo-wells in the continental slope basins (Figure 3.1b). Well and pseudo-well locations along the West Iberian margin were selected based on their relative location on the margin and the reliability of seismic-stratigraphic interpretations, in the case of the pseudo-wells (Figure 3.1b).

Well Lu-1 was a wildcat drilled by Pecten in 1985 on the upper part of the continental slope off Porto (Figure 3.1b). Well Lu-1 targeted a faulted anticline with an Upper-Middle Jurassic carbonate build-up reservoir at its crest. The well has a total depth of 4040 m (TD) and penetrates strata from the Late Triassic (Silves Formation) up to Lower Cretaceous strata (Cacém Formation) (Figure 3.3).

Well 5A-1 was the fifth well drilled in 1975 by Shell Prospex Portuguesa on the continental shelf off West Iberia, to the SW of the city of Porto (Figure 3.1b). Well 5A-1 was drilled on an anticline draped over a block faulted basement. The well has a total depth of 2626 m (TD) and drilled the entire sedimentary sequence down to metamorphic basement (Figure 3.3).

Well Ca-4 was drilled by Texaco approximately 60 km northwest of Porto (Figure 3.1b). Well Ca-4 aimed to drill a large anticlinal closure offset by a series of NNW trending normal faults generated in Late Jurassic – Early Cretaceous strata. The well has a total depth of 2749 m (TD) and penetrates Upper-Middle Jurassic strata through to the Upper Cretaceous (Figure 3.3).

The well models were built using data from completion reports and geophysical logs (e.g. neutron porosity, sonic and density logs). Palaeoenvironmental data indicate that throughout the Mesozoic and Cainozoic the proximal wells experienced neritic (shelf) depositional environments (< 200 m) except for Lu-1 located on the continental slope (see Cunha (2008) and supplementary table 1 for details on data utilised and associated uncertainties).

Three (3) pseudo-wells were compiled in areas with robust seismic stratigraphic markers following the interpretation in Alves et al. (2006; 2009) and Alves and Cunha (2018). In essence, relative dates for seismic and stratigraphic units were based on known information from borehole and outcrop locations, and on published and unpublished information from the Lusitanian Basin (Wilson et al., 1989; Hiscott et al., 1990; Alves et al., 2003a, Alves et al., 2003b; Dinis et al., 2008; Turner et al., 2017), the Porto Basin to the north of this latter (Moita et al., 1996), the Iberia Abyssal Plain (Wilson et al., 1996; 2001; Eddy et al., 2017), and proximal parts of NW Iberia (Groupe Galice, 1979; Boillot et al., 1989; Murillas et al., 1990; Tucholke and Sibuet, 2007). The average palaeobathymetry for the pseudo-well models was constrained by biostratigraphic and lithological data from Lu-1 (before Cretaceous) and DSDP Site 398 (Cretaceous–Cainozoic) (Figures 3.2 and 3.3). DSDP Site 398 is located offshore NW Portugal, and comprises important biostratigraphic and stratigraphic information from Cretaceous–Cainozoic (Groupe Galice, 1979) (Figure 3.3), and this has allowed reliable constraints to be drawn for pseudo-wells 1-3.

The pseudo-wells considered in this work extend to the acoustic basement, which is inferred to be Late Triassic in age (Figure 3.2). The backstripping calculations (interpreted palaeobathymetry for the pseudo-well models) are largely constrained by DSDP Site 398 down to the Barremian, below which level assumptions were made that Jurassic palaeo-water depths in the offshore locations were greater than those calculated from the Lu-1 (see Supplementary Table 1 for input parameters). Rapid increase of palaeowater depth during the Late Jurassic-Early Cretaceous was also accounted for as a result of advanced rifting leading to continental breakup (e.g. Alves and Cunha, 2018).

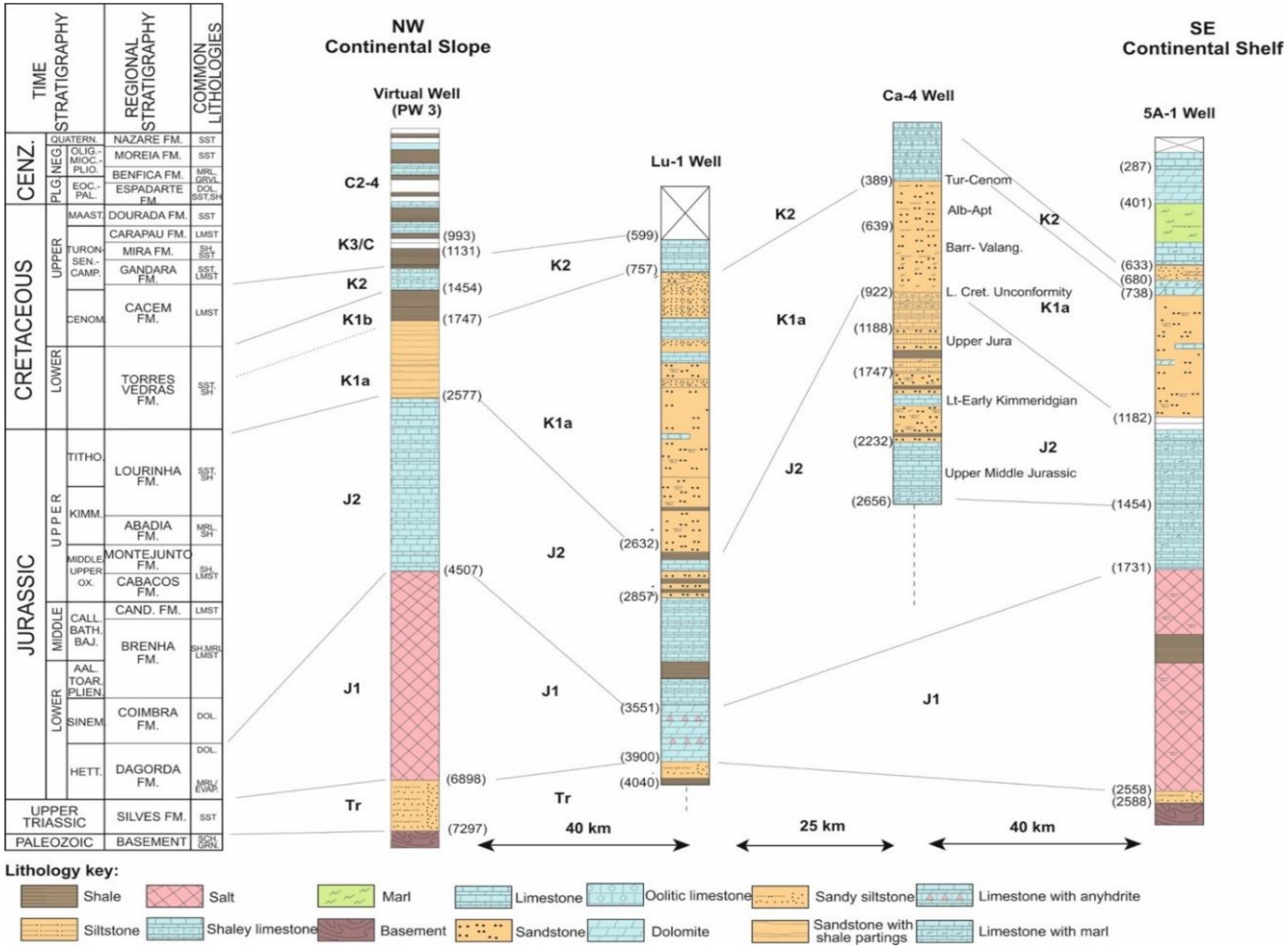


Figure 3.3: Lithological data for individual wells drilled in the Porto and Peniche Basin areas. Note the presence of Triassic continental deposits, late Triassic-early Jurassic evaporites and finally marine Jurassic strata to comprise a tripartite stacking pattern of depositional facies.

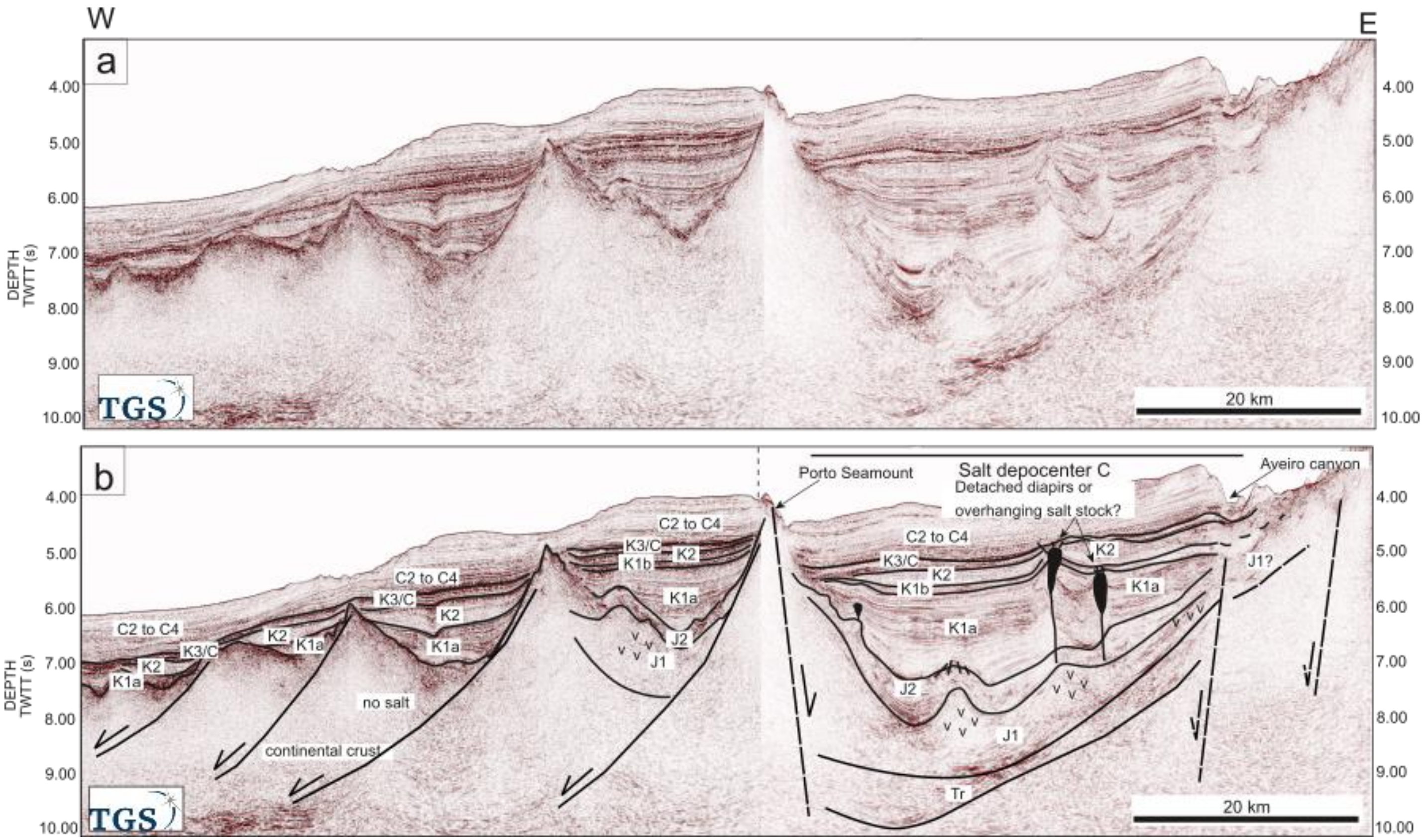


Figure 3.4: a) Uniterpreted composite line b) Interpreted seismic profile of composite line (location shown above). Note structure of Peniche Basin and adjacent deep margin area. Upper Cretaceous Unit K1 is widespread along the margin. Note the disappearance of salt west into the deep margin area. TWTT = Two-way travel time.

3.5 Seismic interpretation of the Jurassic Seaway

Eight seismic units were interpreted in the study area. These units have their age, internal character, thickness and lithology summarised in Table 2.

3.5.1 Unit Tr (late Triassic)

Unit Tr is the basal seismic stratigraphic unit in the study area (Figure 3.2). Its top (Horizon H1) coincides with a high amplitude surface interpreted to be the top of the Triassic strata. Borehole data shows this unit to correlate with continental (and minor evaporitic) deposits of the Silves formation, outcropping in the Lusitanian Basin and drilled on the continental shelf. In the new seismic data used in this work, it is possible to distinguish the boundary between salt and older strata with some confidence (e.g. Figure 3.5).

3.5.2 Unit J1 (?latest Triassic-Hettangian)

Unit J1 is the primary seismic unit addressed in this chapter. It is bounded at its base by Horizon H1. Chaotic to transparent packages predominate in Unit J1, although some high-amplitude internal reflections occur in places. Unit J1 has been interpreted as comprising Late Triassic–Hettangian evaporites (Alves et al., 2006; Rowan, 2014). Its thickness ranges from 750 to 2500 ms TWTT, reaching 3500 ms TWTT within the most developed salt diapirs (Figure 3.7). Unit J1 relates to the first episode of rifting (Rift 1) between West Iberia and Canada (Alves et al., 2002).

Unit J1 is bounded at its top by Horizon H2, the internal character of this horizon is variable due to the effect of the deformed salt. Unit J1 correlates with the top of Unit T/J1 in Alves et al. (2006); however, its basal limit differs to that of the latter authors as it is interpreted with more confidence due to the improved resolution and penetration of the new reprocessed seismic data (Figure 3.5).

3.5.3 Unit J2 (Sinemurian to Kimmeridgian)

Unit J2 is defined at its base by Horizon H2 (Figure 3.2) and consists of high-amplitude reflections, with most internal reflections being relatively continuous but often tilted. Unit J2 shows growth onto fault bounding tilt blocks (Figure 3.5). The unit forms a thick syn-rift package up to 1080 ms in thickness in discrete sub-basins. This increase in thickness is associated with a phase of more gentle, regional subsidence, as discussed later in this chapter.

Unit J2 was first defined by Alves et al. (2006) and its geometry, stratigraphic position and internal character relate it to the J2 megasequence in the northern Lusitanian Basin (Alves et al., 2002). It comprises Middle to Upper Jurassic syn-rift strata. Unit J2 relates to the second episode of rifting in West Iberia (rift 2).

Unit K1a (Tithonian to early Aptian)

Unit K1a is defined at its base by Horizon H3, a high amplitude negative reflection that likely indicates a regional flooding surface. Unit K1a is also bounded at its top by Horizon H4, another continuous and unconformable high-amplitude negative reflection (Figure 3.2). Unit K1a shows a typical rift-related geometry as defined by Prosser (1993). Unit K1a is also bounded by H2 in areas with mature diapirs, where it was deposited into bowl-shaped depocentres between diapirs, indicating that halokinesis accompanied sedimentation. Unit K1a is largely made up of transparent reflections interpreted to be fine-grained strata, with minor high-amplitude continuous reflections interpreted to be coarse-grained units. This unit is interpreted to comprise marine strata, mainly muddy to sandy turbidites as drilled at DSDP Site 398 (Groupe Galice, 1979).

Unit K1a was first defined by Alves et al. (2006), who suggested it to comprise upper Berriasian-Aptian strata based on stratigraphic correlation with a pelagic-sediment-rich seismo-stratigraphic unit at DSDP Site 398 (Group Galice, 1979), and a Valanginian syn-rift turbidite unit at ODP Leg 103. In this work, we extend the base of this unit to syn-rift strata associated with the last continental rifting event in the Jeanne d'Arc Basin in Newfoundland, which started in the Tithonian (Sinclair, 1995). Unit K1a is also associated with the last rifting episode affecting West Iberia (Rift 4).

3.5.4 Unit K1b (Aptian)

Unit K1b is bounded at its base by Horizon H4, interpreted to be a Mid-Aptian Unconformity. Strata onlap onto this surface (Figure 3.5). In contrast with the interpretation of Alves et al. (2006), which assumed this unit as part of K1 (from Alves et al., 2006), it appears that this unit does not contain growth strata and presents a clear facies change from unit K1a below. It represents the basal package of the breakup sequence, and is markedly regressive in nature (de Graciansky and Chenet, 1979; Réhault et al., 1979; Alves and Cunha, 2018). Internal reflections are transparent and in places chaotic, but appear to be relative flat when compared with Unit K1a. Unit K1b is bounded at its top by Horizon H5 (Figures 3.5 and 3.6).

3.5.5 Unit K2 (Albian to Cenomanian)

Unit K2 is bounded at its base by Horizon H5, a high-amplitude surface marking the base of the Albian Black Shales as defined by de Graciansky and Chenet (1979) (Figure 3.2). This horizon comprises a seismic reflection previous interpreted as a break-up unconformity by Groupe Galice (1979) and Réhault et al. (1979). This unconformity is now redefined as being at the base of Unit K1b, i.e. relatively older that previously assumed.

Unit K2 is bounded at its top by Horizon H6, a high amplitude reflection that coincides with the top of carbonate-rich Cenomanian-Turonian strata. Unit K2 comprises a distinct basal seismic sequence of low-amplitude, progradational clinoforms and an upper sequence of high-amplitude continuous parallel reflections. Unit K2 truncates Units J2/3 and K1 in places (Figure 3.5).

3.5.6 Unit K3/C (Turonian-Middle Eocene)

Unit K3/C is bounded at its base by Horizon H6 and at its top by Horizon H7 (Figure 3.5). It comprises transparent to low-amplitude internal reflections, and its average thickness is 100 ms. Stratigraphic information from DSDP Site 398 suggests this unit ranges in age from Turonian up to middle Eocene, including fine to coarse-grained turbidites and pelagites (Alves et al., 2006). This unit marks the oldest drift (or post-breakup) strata on the continental slope of West Iberia (Figure 3.2).

3.5.7 Unit C2-C4 (Late Eocene-Holocene)

Unit C2-4 comprises strata overlying Horizon H7, up to the sea floor (Figure 3.5). It includes the Units C2 and C3/4 from Alves et al. (2006). Its base coincides with Horizon H7, which marks the base of the Cainozoic strata, in the study area (Figure 3.2). Strata in this unit comprise of siliciclastic hemipelagites, turbidites, contourites and nannofossil oozes (Alves et al., 2006).

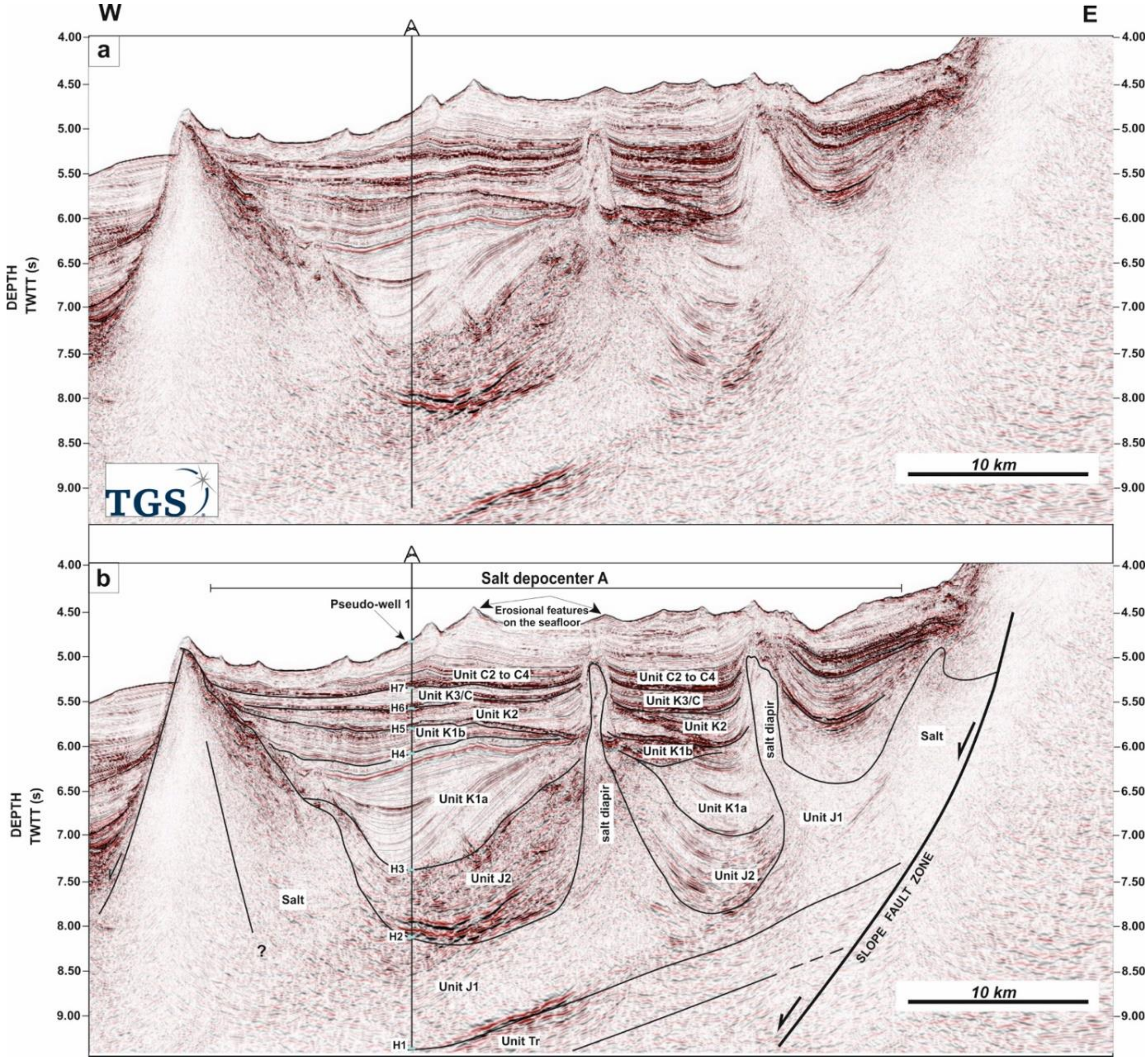


Figure 3.5: a) Uninterpreted E-W section, and b) corresponding interpretation of a seismic profile acquired 50 km southwest of the Porto Seamount. Note the developed diapirs, the clear base of salt and apparent formation of bowl-shaped depocentres during the Early Cretaceous rift 4 (Unit K1). See Figure 3.1b for location. Location of pseudo-well 1 (PW1) shown in this figure.

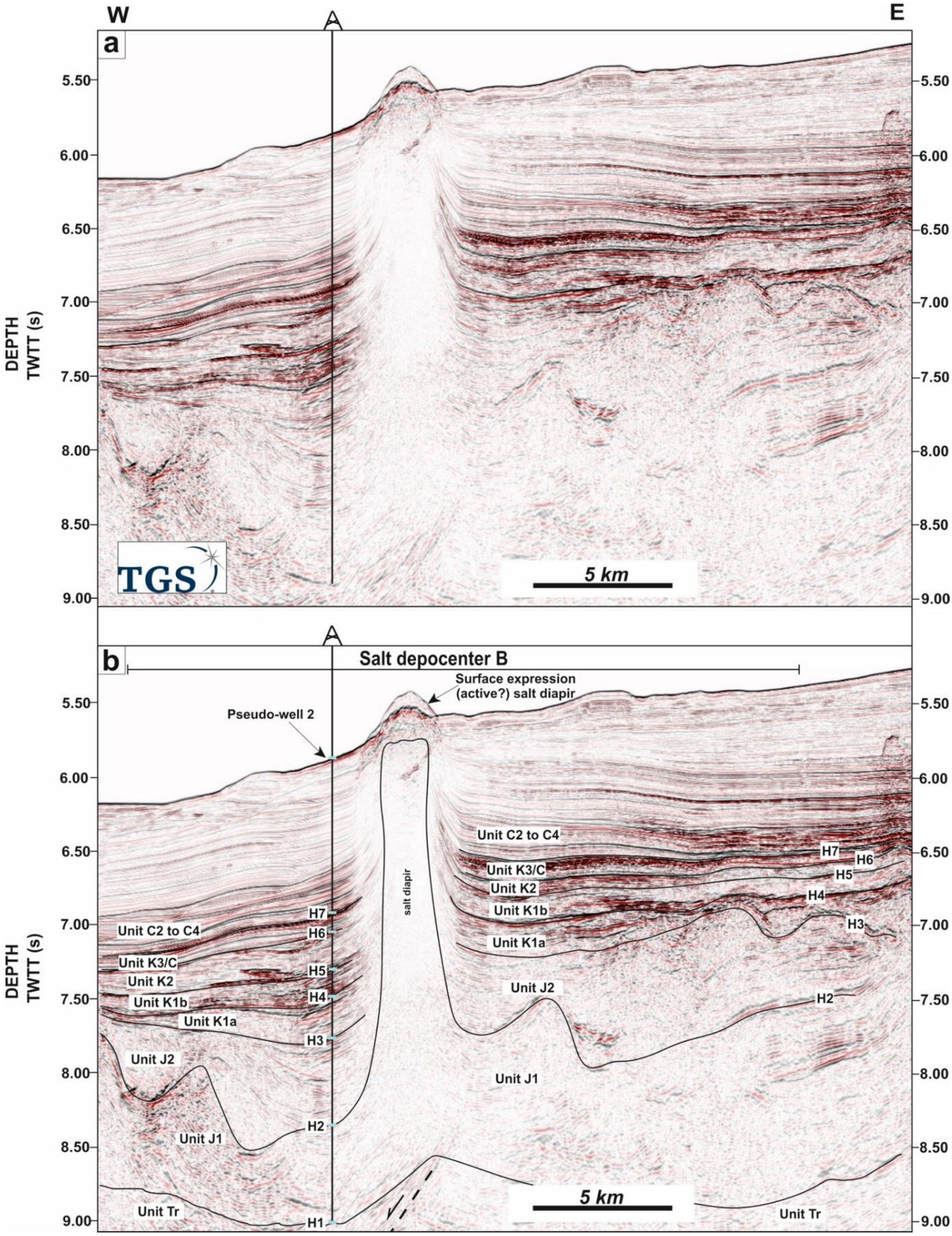


Figure 3.6: a) Uninterpreted E-W section, and b) corresponding interpretation of a E-W seismic profile located to the west of the Porto Basin. See Figure 3.1b for location. Note the surface expression of a developed salt diapir. The location of pseudo-well 2 (PW2) is also shown.

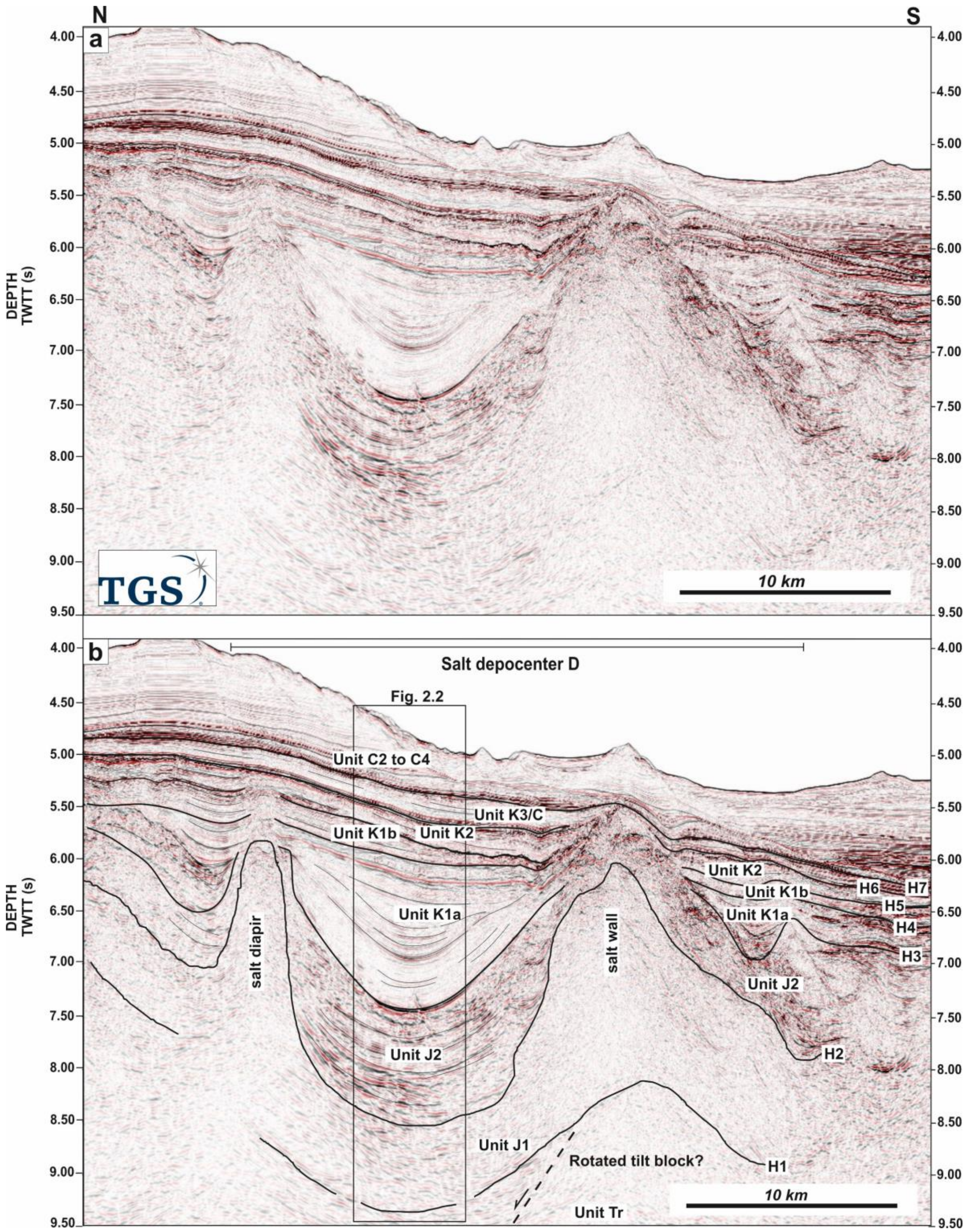


Figure 3.7: a) Uninterpreted section, and b) corresponding interpretation of a N-S seismic profile to the west of the Lusitanian Basin, on the continental slope. See Figure 3.1b for location. Note the presence of developed diapirs and the apparent formation of bowl-shaped depocentres during the Early Cretaceous rift 4 (Unit K1).

3.6 Salt distribution in Continental-slope Basins of West Iberia

The structural fabric of West Iberia follows the trend of Variscan basement faults according to seismic reflection and bathymetric data (Capdevila and Mougenot, 1988). Therefore, the Slope Fault System (SFS) of West Iberia comprises major N-S to ENE-WSW striking faults that bound the continental slope. Faults with similar strikes also control and separate Mesozoic tilt blocks on the continental slope and rise. In the study area, primary fault sets strike NE-SW and include large slope-bounding faults (SFS in Figures 3.5 and 3.8) that cut through the continental slope to separate a shallow continental shelf from deeper continental slope basins. These faults can reach 150 km in length and divide the continental slope into westward tilting terraces at present (Alves et al., 2006). A secondary set of faults show NNW-SSW and N-S strikes (Figure 3.8).

Figure 3.8 shows how salt thickness in TWTT was mapped so as to document the distribution of salt across the study area. The average salt velocity calculated from wells in the area approaches 4.5 km/s, as estimated from Well Lu-1 (Figure 3.3). In the study area, early Mesozoic salt has a thickness ranging from 750 to 2500 ms TWTT in distinct sub-basins, reaching 3500 ms TWTT within the most developed salt diapirs. Therefore, salt thickness away from diapirs, ranges from approximately 1.7 km to 5.5 km, with mature diapirs comprising up to 7.5 km of salt in their interior (Figure 3.8). The width of the salt reaches 40 km across salt-rich basins on the continental slope (Figure 3.5). To the east, the early Mesozoic salt terminates against the Slope Fault System bordering the continental slope. Well Lu-1 located on the slope, primarily records dolomitic strata with minor salt, while well 5A-1 on the continental shelf, records the presence of 800 m of evaporites (Figure 3.3). Further offshore, to the west of the study area, seismic data close to DSDP Site 398 do not reveal the presence of salt west of the continental slope basins defined by Alves et al. (2006) (Figure 3.8). Such a salt distribution highlights a key feature; early Mesozoic salt in West Iberia follows a NE-SW trend that is confined by the structural lineaments and fault systems that segment the continental slope (Figure 3.8).Four main salt depocentres were identified in the region west of the Slope Fault System (Depocentres A-D).

In these depocenters, halokinesis is related to regional extension and half-graben collapse relative to the SFS, conditioning the development of discrete salt structures. This type of salt tectonics is common in active rift basins, and on the outer shelf and upper slope of passive margins (Hudec and Jackson, 2007). Where precursor diapirs are absent, thickness of the evaporite deposit is the main control on structural style. Above thick salt, diapirs and adjacent withdrawal basins grow larger. Depocentre A is 25 km wide and mature diapirs form bowl-shaped depocentres for Jurassic and Lower Cretaceous strata (Figures 3.5 and 3.8). Here, diapirs reach 3500 ms TWTT, or 7.5 km. The two mature diapirs interpreted in depocentre A show growth that is limited to the Cainozoic strata (C2-C4), narrowing at the head of the diapirs. Such a geometry reveals that abundant salt fed the diapir, which began to widen the deeper parts of the crest prior to widening the younger crest (Hudec and Jackson, 2007).

Depocentre B comprises one large diapir with a clear surface expression; salt availability allowed this diapir to grow reactively near or up to the surface (Figures 3.6 and 3.8). The much larger Depocentre C forms a 46 km wide salt basin filling a landward-dipping half-graben bounded to the east by the Slope Fault System (SFS) and to the west by the Porto Seamount (Figures 3.4 and 3.8). Here, developed salt stocks are found in Cretaceous and Cainozoic strata, whereas salt pillows do not impinge on Cretaceous strata, forming Jurassic minibasins instead.

Depocentre B and C are likely dextrally offset from Depocentre A from the west by the westward projection of the Aveiro Fault. Depocentre D is a 27 km wide diapir-bounded bowl-shaped depocentre mostly filled by Jurassic and Lower Cretaceous strata (Figures 3.7 and 3.8).

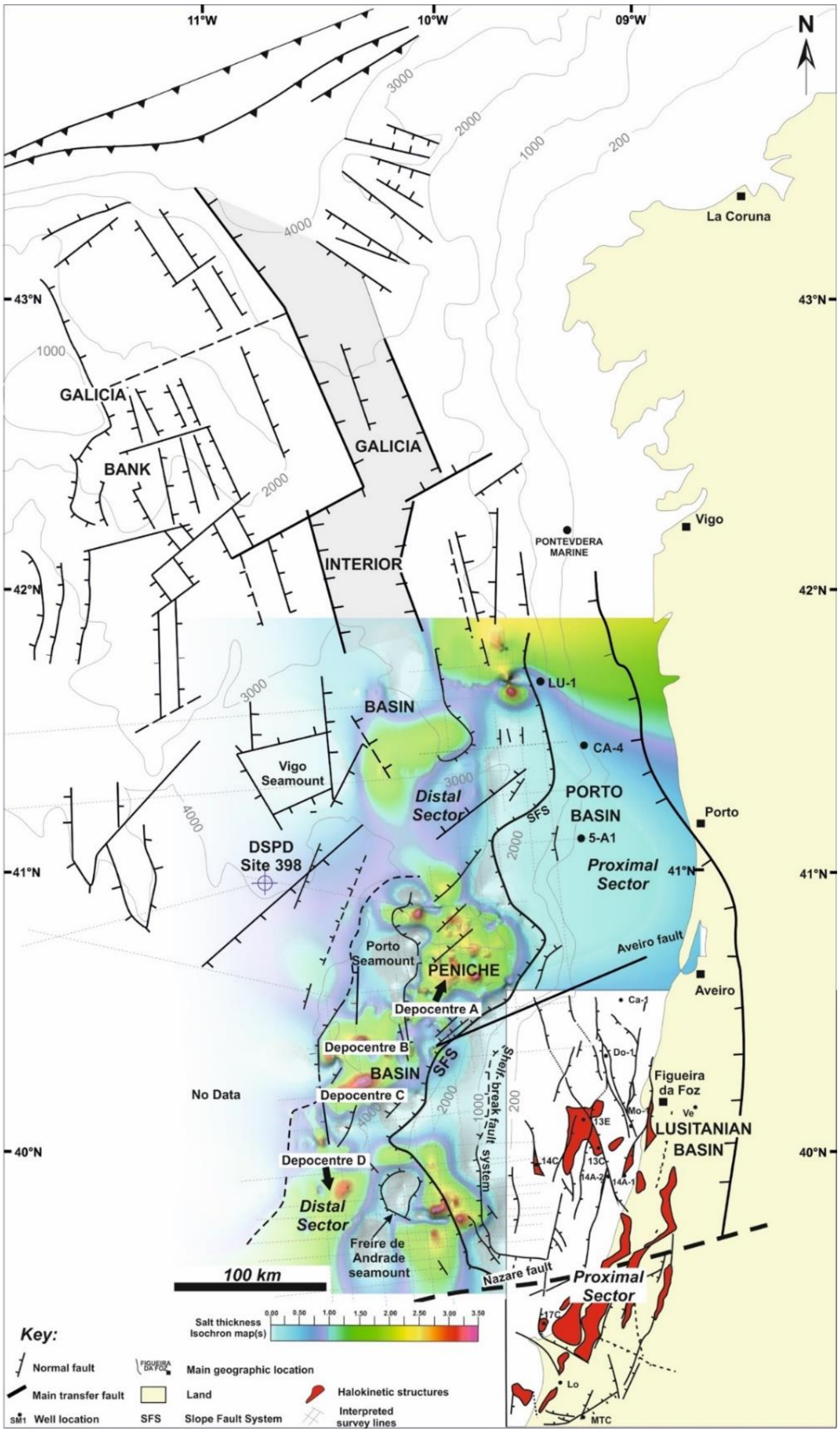


Figure 3.8: Salt thickness map in TWTT, from Horizons H1 to H2, overlain by structural elements from Alves et al. (2006) and Murillas et al. (1990). Also shown is the interpreted seismic grid. Inset map is taken from Alves (2002) highlighting halokinetic structures mapped east of the study area, in the Lusitanian Basin.

3.7 Subsidence Models: Deep offshore vs. Continental shelf

3.7.1 Continental shelf (exploration wells)

All modelled exploration wells reveal important basement subsidence during Late Triassic-Early Jurassic rifting, followed by further deepening due to relative post-rift tectonic quiescence through the Middle Jurassic (Figure 3.9a-c). Subsidence models for Well 5A-1, on the continental shelf, reveal a depositional hiatus and relative shallowing associated with exhumation of structural highs next to subsiding basins during Late Jurassic–Early Cretaceous rifting (Figure 3.9a). In contrast, Well Lu-1, now located on the upper continental slope records a marked increase in subsidence during that interval (Figure 3.9b), likely due to rifting in the Late Jurassic to Early Cretaceous being focused west of the continental shelf. As a result, the relatively proximal wells (e.g. Well 5A-1) in the Lusitanian Basin record marked differences in their subsidence histories compared to the continental slope basins, including Well Lu-1 (Figure 3.9b).

3.7.2 Continental slope basins (pseudo-wells)

All pseudo-wells reveal very marked syn-rift subsidence in the Late Triassic-Early Jurassic interval. Pseudo-wells 1–3 record more than 2000 m of subsidence during the Hettangian–Sinemurian (Figure 3.9d-f), accompanying the deposition of thick salt, the deep-offshore equivalent of the Dagorda Formation in the Lusitanian Basin, which is robust evidence for the beginnings of a developing seaway here as early as the latest Triassic or Hettangian. The subsidence curves for continental slope basins reveal these to be considerably deeper than the more proximal continental-shelf basins during Late Triassic to Early Jurassic rifting, further highlighting the presence of a major structural feature separating both areas. Middle Jurassic to early Late Jurassic tectonic quiescence is also revealed by the subsidence models, followed by another episode of deepening associated with an increase in palaeowater depths during Latest Jurassic to Early Cretaceous rifting (Figure 3.9d). Subsequent deepening into the Cretaceous is evidence for a seaway that continued to be present during subsequent rifting episodes (Rift 4) (Figure 3.9d-f).

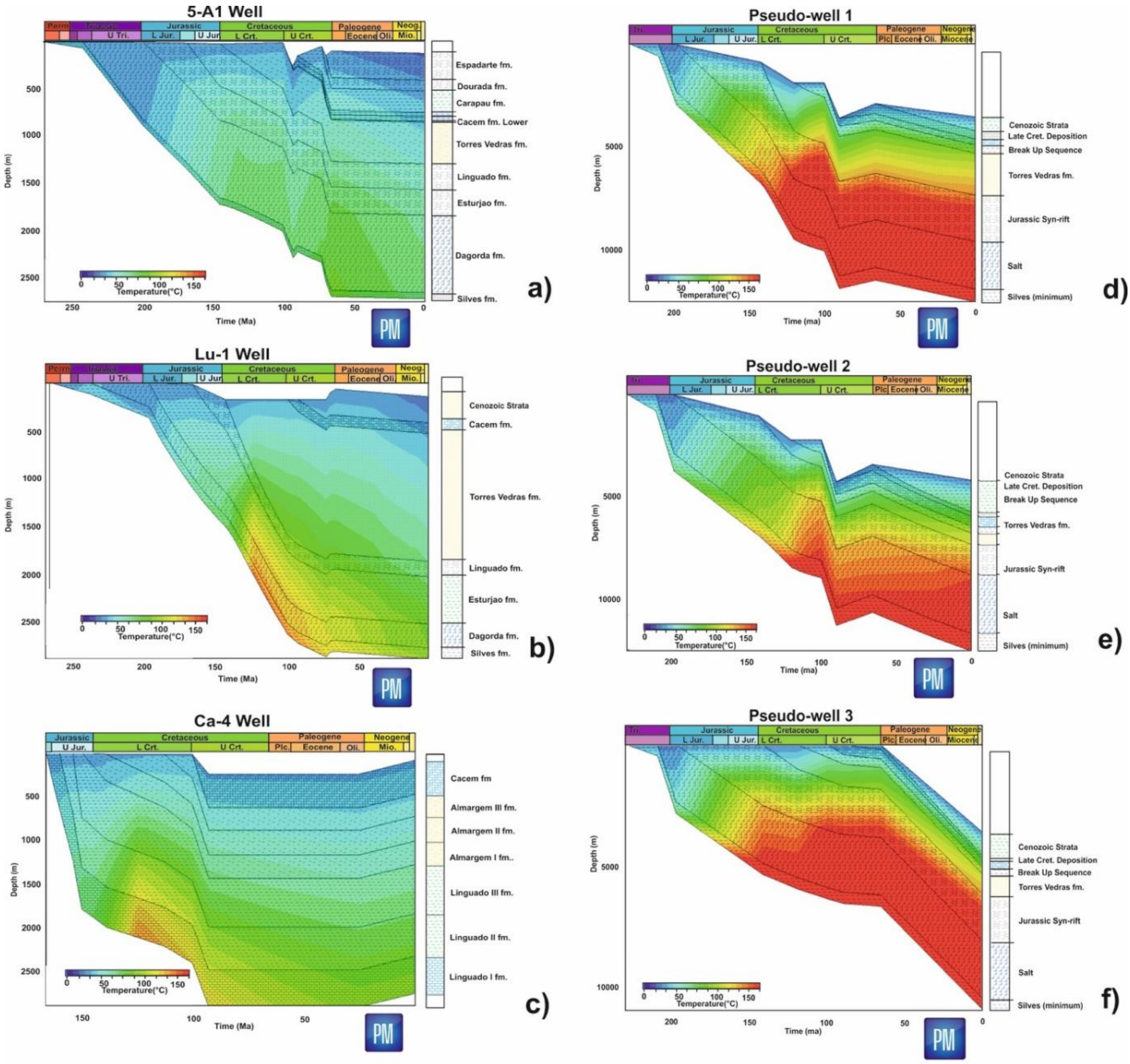


Figure 3.9: a) Thermal subsidence curve for well 5A-1. b) Thermal subsidence curve for well Lu-1. c) Thermal subsidence curve for well Ca-4. All wells located on the continental shelf. d) Thermal subsidence curve for pseudo-well 1, e) Thermal subsidence curve for pseudo-well 2, f) Thermal subsidence curve for pseudo-well 3. Pseudo-wells are located in continental-slope basins to the west of the Lusitanian and Porto Basins. (Locations of pseudo-wells are shown in Figures 3.1b.

3.8 Tripartite stratigraphy in West Iberia

Exploration wells on the continental shelf of the West Iberia Margin record the significant change in deposition that occurred from the Triassic to the Early Jurassic as the seaway was developed, as one within a network, providing the gateway between the Boreal and Tethys Oceans. This tripartite stacked pattern of continental, evaporitic and marine strata records the transition between continental to marine deposition with salt deposition as the intermediary facies (Figure 3.3).

Well 5A-1 penetrated basement at its deepest and encountered 30 m of red micaceous mudstone (Triassic Silves Formation) followed by 814 m of an heterogeneous succession of salt interbedded with mudstone, anhydrite, limestone, mudstone and dolomite layers (Dagorda Formation). Some 13 m of tight dolomite was encountered before a 277 m section of Middle to Lower Jurassic limestone, silty marlstone and stringers of anhydrite, clay and siltstone (Esturjão Formation; Figure 3.3). This reveals the presence of marine incursions in this Early Jurassic seaway. Similarly, completion logs from Well Lu-1 show a minimum of 142 m of continental sandstone, conglomerate and red mudstone (Silves Formation) below a Sinemurian section of interbedded dolomite and anhydrite (Dagorda Formation). These latter evaporites are interpreted to have been deposited in a shallow sea created in the Hettangian. Interbedded limestone and shale were recorded above the Dagorda Formation, followed by a 110 m section of black shale at the top of the succession, deposited as a result of continued subsidence during the Pliensbachian (Figure 3.3).

Correlating our seismic interpretation, the stratigraphy of the continental shelf basins, from south to north, records continental deposition in the Triassic (Silves Formation) followed by Hettangian evaporite deposition (Dagorda Formation) and subsequently followed by marine carbonates and muds deposition in the Sinemurian (Coimbra Formation) and Pliesbachian–Toarcian (Brenha Formation) (Alves and Cunha, 2018; Sêco et al., 2019) (Figure 3.2).

3.9 Seaway models for the Triassic–Early Jurassic of West Iberia

Detailed seismic interpretation reveals, for the first time the presence of an extensive Early Jurassic seaway in this region; the South Laurasian Seaway. Seismic interpretation shows that the thickest salt is confined by four (4) salt depocentres in the distal part of the margin that are bounded to the east by a Slope Fault System and to the west by several seamounts and syn-rift structural highs (Figures 3.5 and 3.8). In this sector of the West Iberian Margin, salt thickness in Early Jurassic depocentres can reach 2500 ms and mature diapirs are observed (Figure 3.8). Lower-Middle Jurassic strata (Unit J2) form syn-rift packages in salt depocentres that are 2.3 km thick in some places (Figure 3.5). According to subsidence models in pseudo-wells 1, 2 and 3 more than 2.5 km of subsidence were recorded west of the Slope Fault System (Figure 3.9d, e, f). It is proposed that this enhanced subsidence was related to a strong phase of Late Triassic to Early Jurassic extension, as shown by the deposition of thick salt followed by the accumulation of Lower-Middle Jurassic strata partly influenced by the main phase of halokinesis, as well as continued extension related to rifting (Figures 3.5 and 3.9d, e, f).

Seismic interpretation at DSDP Site 398 has revealed a distinct lack of salt structures (Figure 3.4). It is plausible to consider that salt disappears roughly west of the Porto Seamount where, at this location, only a small amount of salt is present (Figure 3.4). Seismic interpretation also revealed that the continental Slope Fault System delimits the area of thick salt deposits on the continental slope from the shallower Lusitanian Basin (Figure 3.8). However, analysis of industry wells on the continental shelf has revealed that Upper Triassic to Lower Jurassic salt is also present here, albeit with thicknesses that are significantly less than those to the west of the Slope Fault System (Figure 3.3). According to our subsidence models (Figure 3.9a, b, c) a similar pattern of subsidence to the continental shelf occurred in continental-slope basins, but the former show total subsidence values that are three times smaller (850 m) when compared to the latter (2500 m). Hence, a key finding in this work is that subsidence models reveal that the seaway of interest to this study was divided into two sectors (distal and proximal) by the Slope Fault System as early as the Late Triassic and Early Jurassic; their different subsidence histories prove the existence of such a division. Such a character is also typically recorded in basins where syn-stretching salt is deposited, as defined by Rowan (2014), where evaporites are found in varying thicknesses and extent over the margin due to its early deposition during rifting.

Further east in the northern Lusitanian Basin, latest Triassic to Early Jurassic salt is recorded in multiple exploration wells and at outcrop (Alves et al., 2002) (Figure 3.8). Salt accumulations in the Lusitanian Basin are bounded to the east by the Porto-Tomar Fault (Pinheiro et al., 1996; Soto et al., 2012). It is proposed in this work that the Jurassic seaway included the Lusitanian Basin and, therefore, spanned from this latter basin to the vicinity of the Porto seamount, reaching a width of ~ 200 km (Figure 3.8).

Exploration wells in the Porto Basin, seismic interpretation in the Peniche Basin, and outcrop observations in the Lusitanian Basin, have documented shared terrestrial, evaporite and marine depositional patterns. Similarly, north of the study area, in the Galicia Interior Basin, there is evidence of earliest Jurassic strata with shallow marine facies as pointed out in Murillas et al. (1990) and proven by dredge samples from seamounts off Galicia and Portugal (Alves, 2002). The Galicia Interior Basin is itself considered as part of a Triassic rift system formed between Europe and Laurentian Pangaea, formed prior to the opening of the Central Atlantic around the Bathonian-Callovian (e.g. Klitgord and Schouten, 1986). Basins recording similar times for early syn-rift extension occur in Newfoundland, offshore eastern Canada, and along the continental shelf of Portugal, Spain and west of France. As also stated in Murillas et al. (1990), the transition between the Porto Basin and the Galicia Interior Basin has been poorly defined in old, vintage seismic data where bottom multiples obliterate nearly all the primary reflections at the depth of occurrence of Upper Triassic to Lower Jurassic strata. However, the data in the present work show the northernmost areas of the continental slope to comprise local depocentres with thick salt and Jurassic strata, justifying the continuation of the Early Jurassic seaway towards the NW of Iberia, into Spanish waters (Figures 3.8 and 3.10). In fact, it is now understood that the Porto Basin and its prolongation towards the Galician Shelf, where the exploration wells referred to by Murillas et al. (1990) were drilled, comprise the proximal part of a larger, deeper axis of continental rifting that extends from the continental slope of Portugal towards the Galicia Interior Basin, both delimited by NE-SW and NW-SE faults (Figures 3.5 to 3.8). The tectonic evolution of the Porto Basin and these latter continental-slope depocentres is similar, with syn-rift extension starting in the Early Mesozoic (Triassic to Early Jurassic), and recording their principal extensional episode during the latest Jurassic to Early Cretaceous (Alves et al., 2006; Alves and Cunha, 2018).

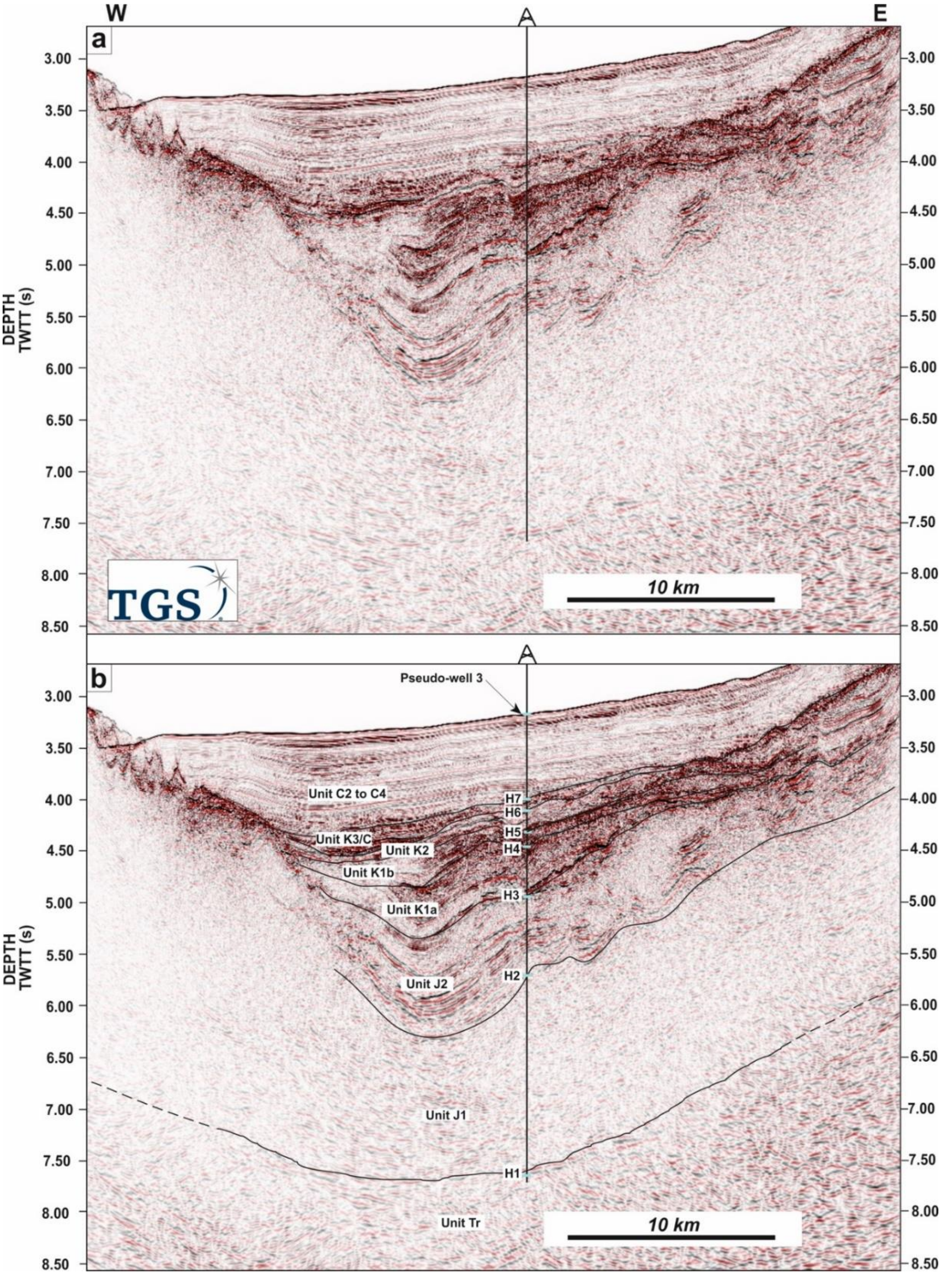


Figure 3.10: a) Uninterpreted E-W section, and b) corresponding interpretation of a seismic profile close to the northernmost part of the study area, into the Galicia Interior Basin. See Figure 3.1b for location. Note the absence of salt structures in this location and interpreted presence of thick salt. Location of pseudo-well 3 is also shown in the figure.

3.10 Chapter specific summary

The data in this study reveals that Triassic–Early Jurassic continental rifting in the North Atlantic coincides with the establishment of a ~200 km wide seaway in West Iberia. New reprocessed data and tectonic subsidence curves for the Lusitanian, Porto and Peniche basins, West Iberia, reveal the palaeo-position and width of this Triassic-Early Jurassic seaway, which was divided in two distinct sectors. In conclusion, the major findings of this chapter are as follows:

1) The thickness of the West Iberian salt was quantified for the first time, varying from 1.7 km to 2.5 km in the main depocentres of continental-slope basins. This, and an overlying thick succession of Lower-Middle Jurassic strata, indicate the presence of a South Laurasian seaway relatively wide and extending into what are, at present, continental-slope basins.

2) The marked Early Jurassic subsidence observed in the in the salt-rich depocentre reaches over 2000 m by the Hettangian and contrasts with the results from exploration wells drilled on the continental shelf. These more proximal wells recorded a maximum of 800 m of subsidence at this time, a character emphasising how partitioned this seaway was.

3) Continued tectonic subsidence throughout the Early Jurassic is estimated based on tectonic subsidence models, recording a maximum of 5 km in the offshore Peniche Basin. This value compares with the 1.1 km in the proximal Lusitanian Basin.

4) Tripartite continental, evaporite and marine facies associations spanning the Late Triassic to Early Jurassic in West Iberia, record the development of the seaway in this location, the south Laurasian Seaway.

5) This same tripartite stratigraphy is recorded in other parts of the North Atlantic, albeit with different ages in places. Hence, it is proposed that tripartite facies associations are an indicator of a common stratigraphic record of seaway formation all over the North Atlantic realm.

This study proposes that the common tripartite stacking pattern recorded in various Mesozoic basins across the North Atlantic is an indicator of a common stratigraphic record of one or several seaways existing during the latest Palaeozoic to early Mesozoic. Furthermore, we postulate that the continental-evaporite-marine succession exists in association with the generation of isolated depositional basins in seaways first filled with evaporites rather than marine deposits. Distinct palaeogeographic and geological settings for the different seaways considered in this work, formed in an early North Atlantic region, have therefore implications to the perhaps 'unique geological conditions' in which the Pangea continent was rifted.

4 Geochemical findings from Upper Jurassic rocks in the Central North Sea

4.1 Abstract

This work uses IGI ltd. Geochemical database of the North Sea to study some geochemical character markers of source rocks in the Norwegian Central Graben of the North Sea during the Upper Jurassic to reveal their organic matter composition from the beginning of the continental rifting phase in the Upper Jurassic through to its end. Using kerogen type I II III, as well as several supporting biomarker analyses, as a proxy for the presence of terrestrial or marine organic matter during deposition. Revealing that a persistent terrestrial influence alongside marine inputs across multiple formations, from the early Sleipner to the later Draupne, Tau, and Mandal formations, with a notable terrestrial signature in the Kimmeridgian-Tithonian Farsund Formation. This evidence suggests a complex interplay between local tectonic regimes, sedimentary processes, and eustatic changes, underscoring the necessity of regional specificity in predictive modelling for hydrocarbon exploration.

Comparisons of biomarker analyses into samples of Kimmeridgian-Tithonian of the Farsund Formation in two locations across the Central Graben area also show an increased terrestrial signature in one compared to the other. This would be interesting for future work, to consider organic matter sources spatially and mapping proximities to them, for example, mapping dynamic changes in terrestrial source during rifting via geochemical methods.

4.2 Introduction

Petroleum source rocks are not evenly distributed in the rock record with major transgressions, warm equable climates and anoxia playing key roles in their appearance in the rock record. Most favourable past times for source rock deposition include the Silurian, Late Devonian, Late Jurassic and Cretaceous (Peters et al., 2005). Long gone is the notion of the Jurassic and Cretaceous being a time of monotonously warm equable conditions and sluggish ocean circulations and has given way to a more varied view of palaeoclimate and oceanographic conditions, especially during the Late Jurassic and Early Cretaceous (Mutterlose et al., 2001).

After more than 50 years of exploration in the North Sea, several intervals and formations with source rock potential in the North Sea have been identified. Justwan et al. (2005) suggested four formations in the nearby Southern Viking Graben with source rock potential:

• Middle Jurassic *Sleipner Formation* and *Hugin Formation*: Local coal beds within these formations contain high values of TOC and they are consequently prone to gas and volatile oil (Isaksen et al., 1998);

• Middle to Upper Jurassic *Heather Formation*: Variable organic facies has resulted in the deposition of kerogen types II, III and IV, as well as degraded marine material. Sub-optimal preservation conditions and average TOC of 2-4% has put substantial limits for oil generation (Thomas, et al., 1985);

• Upper Jurassic to Lower Cretaceous *upper and lower Draupne Formation*: TOC in the range of 5-12% (Thomas, et al., 1985). The syn-rift deposited lower part feature a mix of type II and III kerogen in addition to more gas prone and inert organic matter (Justwan, et al., 2006). Post-rift thermal subsidence caused less mass flow influence during deposition of the upper part, resulting in an oil-prone kerogen type II (Justwan, et al., 2006).

The definition of a source rock is a sedimentary rock able to generate a significant volume of oil and/or gas (Cornford, 1998). A working source rock is typically an organic-rich, dark and laminated mudstone or shale. Demaison and Moore (1980) describe the typical depositional environment for such rocks. The required anoxic environments are the result of higher oxygen demand than oxygen supply in the water column. It is the depositional conditions and primary organic material provided during source rock formation that dictate the organic matter type incorporated into the source rock. Better understanding of the organic matter composition of potential source rocks therefore incurs a better understanding on future predictability and essentially yield if is to become a working source rock with the other requirements having been met.

A typical source rock may contain 1% organic matter. Photosynthesis is the greatest means by which new organic matter is synthesised, it is the primary source for biomass in almost all living organisms and accounts for most organic matter buried in rocks. Organic matter is composed of four main constituents, lipid, proteins, carbohydrate and lignin. Photosynthesising organisms are restricted to land and the photic zone in lakes and oceans because energy from light is required for photosynthesis. The organisms that do this are called phototrophs, phototrophic microorganisms such as plankton and algae are most important in aquatic environments, whereas higher plants dominate the land. This fundamental difference in dominant contributing phototrophs, affects the type of organic matter ultimately deposited in source rocks. Other vital factors that contribute to a good source rock are; high organic productivity to increase amounts of organic matter that can be accumulated and the preservation of that material (reduced degradation) which can be achieved by anoxic conditions and rapid burial and finally evolution of organic matter during burial through to kerogen, bitumen and oil/gas maturation.

Several rift-related rock units in the Norwegian Central North Sea area that span the Upper Jurassic are studied here from a geochemical viewpoint, adding to the myriad of data south of the formerly 40 degree N latitude Boreal realm. It is also providing a contrast with the tectonic and lithological viewpoint of this thesis' previous data chapter, wholly in the context of continental rifting. In this chapter we display geochemical data in rock samples through time and space to show their bulk-rock compositions as well as look at some key biomarker distributions, to give insights into organic matter type and any inferred depositional controls and environments using pre-derived graph layouts from IGI ltd. Software pIGI.

Specifically, we were seeking answers to the following questions:

1. What geochemical signatures can be identified in rock formations to deduce organic matter type?
2. How does organic matter type change, during rifting?

4.3 Chapter specific data and methods

The geochemical database and associated sample information used for this study is part of a larger single geochemical database compiled for the Norwegian North Sea using pIGI software

(IGI Ltd.) 2017. The database spans 718 wells drilled on the Norwegian Continental Shelf between 56'N and 62'N and comprises of 52978 data samples including rock, oils, gases and condensate sample types. It was built using many geochemical reports for wells, from different laboratories, available on the Norwegian Petroleum Directorate and underwent several protocols and quality check processes to build the database accurately. For example, the complexity of vast quantities of samples handled by different labs at different times using opposing nomenclature, in some cases. These protocols and checks allowed for the original integrity of the samples to be maintained. For every sample the database has stored key information such as the well it was obtained from, the depth at which the sample was collected, the lithostratigraphic interval associated with that depth, it's age, its lithology type, as well as results from a range of different geochemical analyses such as TOC, Rock-Eval, Vitrine Reflectance, Gas chromatography, Sterane biomarkers, Hopane biomarkers, Bulk isotopes and Gas isotopes.

Due to the 'Upper Jurassic source rock evaluation' focus of this study, three main tasks were conducted to comprise a subset of the main geochemical database on which to work on: 1) removal of oil gas and condensate samples, leaving rock samples (core, sidewall core and cuttings); 2) removal of samples that were not of Upper Jurassic age, for the purpose of this study the samples range in age from the Bathonian (Mid Jurassic)-Berriasian (Lower Cretaceous); 3) Quality/integrity check process to exclude samples that were most likely to be oil-stained or contaminated. A total of 993 rock samples were considered in this study, from a total of 73 wells around the Norwegian Central Graben of the North Sea (Table 4.1). The various wells were assigned to 10 major structural elements based on their locations and information from NPD website.

For this study several source characteristics and their associated graphs were selected to display findings and trends in the study area in the upper Jurassic. In this section the origin and utilisation of these characteristics will be explained.

Basin	Well	No. of samples
Utsira High	15/6-8S	9
	16/2-6	1
	16/3-4	5
	16/4-2	61
	16/7-2	6
	25/10-2R	6
	25/11-15	1
	25/5-3	3
	25/6-1	20
	25/6-2	7
	25/8-7	4
	25/9-1	7
	25/9-3	7
Sorvestlandet High	2/1-12	16
	2/1-2	13
	2/2-2	10
	2/2-5	1
	2/3-4	1
	3/4-1	7
	8/10-1	2
	8/10-2	7
Steinbit Terrace	2/2-1	14
	2/2-4	2
	2/4-8	2
	2/5-1	8
	2/5-7	1
	2/5-9	2
Maureen Terrace	15/12-10 S	19
	15/12-12	5
	15/12-4	10
	15/12-5	7
	15/12-6 S	11
	6/3-1	1
Ling Depression	15/12-1	15
	15/12-11 S	4
	15/12-2	12
	15/12-3	33
	15/12-8 A	3
	16/10-1	10
	16/10-2	5
	16/10-3	8
	16/10-4	48
	16/8-2	6
	17/6-1	15

Basin	Well	No. of samples
Jaeren High	15/12-7 S	4
	6/3-2	18
	7/3-1	2
	7/4-1	13
	7/7-2	4
	7/9-1	4
	7/8-2	1
Hidra High	1/3-8	21
	2/4-16	12
	2/4-18 R	3
	2/4-17	32
	2/4-14	14
	2/4-13	10
Feda Graben	1/5-2	1
	1/6-7	5
	1/9-3 R	2
	2/11-7	57
	2/12-1	61
	2/12-2 S	9
	2/7-15	59
	2/8-3	19
Egerund Basin	17/12-1 R	12
	17/12-2	13
	17/12-3	38
	18/10-1	29
	8/3-1	2
	8/3-2	9
	9/2-1	18
	9/2-2	10
	9/2-3	17
	9/2-7 S	9
	9/3-1	45
	9/4-5	4
Breiflabb Basin	17/11-7	1

Table 4.1: Table showing the 10 structural elements with associated wells and number of rock samples from each well, totalling 993 samples.

4.4 Geological Setting of the Norwegian Central North Sea

4.4.1 Physiography of Norwegian Central Graben and marginal area:

The Central Graben of the North Sea developed as one of three arms of a NW-SE trending triple junction rift system, with the Viking Graben and the Inner and Outer Moray firth making up the northern and western arms respectively and The Norwegian-Danish basin is found to its east (Figure 4.1a). The 70-130 km wide and 550 km long Central Graben separates Norwegian basement in the east from the UK continental shelf in the west (Stricker and Jones, 2016). The Central Graben consists of two main grabens the West and East Central Graben divided by the Forties-Montrose Ridge and Josephine Ridge horst blocks in its centre and flanked by platform areas (West Central Shelf and Auk Ridge in the west and Jaeren High, Cod Terrace, Steinbit Terrace, Piggvarr Terrace in the east) (Figure 4.1b).

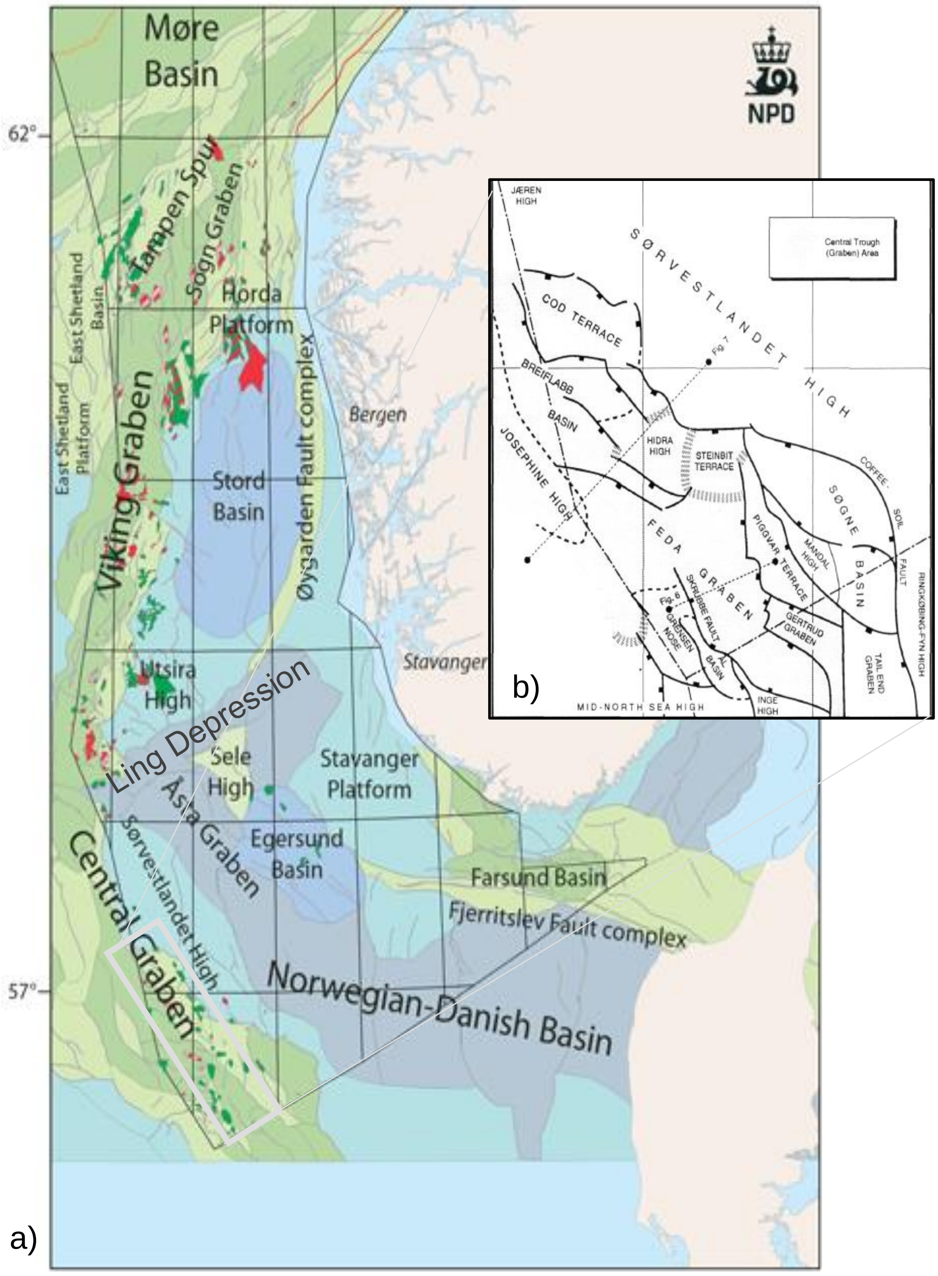


Figure 4.1: a) Map of Norwegian North Sea and geographical location showing main structural elements from NPD Norwegian Petroleum Directorate. b) Structural elements in the Central Graben active during the Jurassic-Early Cretaceous based on Gowers et al. (1993).

The Central Graben is structurally complex because it has been affected by several tectonic phases, these can be grouped into three main phases: 1) Regional flexural uplift during the late Triassic-middle Jurassic; 2) intense segmentation due to faulting during the Late Jurassic to Early Cretaceous that included subsidence, rotation and inversion confined to the central trough area and finally a regional flexural subsidence from the Late Cretaceous to Tertiary (Gowers et al., 1993).

4.4.2 Structural areas studied in this thesis

In this study we focus on various structural elements transecting parts of the Norwegian North Sea with the aim to study and compare the geochemical character of upper Jurassic units from the Utsira high in the North, as far east as the Egersund Basin in the Norwegian-Danish basin, and the Sorvestlandet high straddling the eastern flank of the Central Graben (Figure 4.1 a & b).

The Utsira high is found flanking the base of the South Viking Graben, an asymmetric half-graben of the northern arm of the North Sea trilete rift system (Jackson et al., 2010). The Utsira High is a structural high lacking Permian, Triassic and Jurassic units across much of it, highlighting its persistence as a structural high during the Permo-Triassic and Late Jurassic rifting episodes (Jackson et al., 2010). The Ling Depression is a NE-SW structural feature that is flanked by the Utsira High to the north, while the Egersund basin is found south of the Ling Depression. Both can be considered as second-order structural elements of the Norwegian-Danish Graben, affected by halokinesis, mainly formed during the Late Palaeozoic-Triassic and less influenced by the characteristic North Sea rifting (Hansen et al., 2019). The Jaeren high is located south of the Ling Depression and is flanked to its south by the Central Graben, an eastward tilted fault block mainly comprising Jurassic and earliest Cretaceous strata (Hoiland et al., 1993). The Breiflabb Basin and the Feda Graben are sub-basins of the Central Graben (Figure 4.2). The Egersund basin is located east of the Central Graben (Figure 4.1 a), it's genesis and evolution are inextricably tied to the Late Paleozoic tectonics following the Caledonian orogeny collapse, with subsequent reactivation during the Variscan Orogeny, which was the foundation for the complex structural grain that guided its later development (Kalani et al., 2020). The interplay between these ancient tectonic fabrics and the development of rift-related normal faults during the Permian to Early Triassic periods crucially shaped the Central and Northern North Sea's rift dynamics, thus influencing the depositional systems and potential hydrocarbon traps within the Egersund Basin (Kalani et al., 2020).

4.4.3 Middle to Upper Jurassic stratigraphic framework and structure

The basic structural framework for the North Sea is mainly the result of Late Jurassic-Early Cretaceous rifting, and was partly controlled by older structural elements. It is this tectonic phase that caused the most structural complexity in the study area, playing a key role in establishing the traps for hydrocarbon accumulations that has made the area so important in the exploration industry. The Late Jurassic extension in the central North Sea is characterised by the rifting that spread from the Arctic south, reaching the Viking Graben during the Bajocian-Bathonian and the Central Graben during the Callovian-early Kimmeridgian. It saw major block faulting that caused uplift and tilting, creating local topography with erosion and sediment supply.

The following section describes the main lithostratigraphic groups and associated formations that are present in the studied areas, as these comprise of an assembly of units found in; The South Viking Graben, Central Graben, and Norwegian-Danish Basin. Nomenclature, age, and proposed depositional environments were derived from several sources from the Norwegian Petroleum Directorate (NPD).

Following from the transgression that brought the Triassic to the Jurassic, the uplift of the Aalenian mid-North Sea Dome over the trilete system of the Viking Graben, Central Graben and Moray Firth saw large deltaic systems build out containing sand, shales and coal in the northern North Sea (Brent Group). Similar deltaic systems built out in the Norwegian-Danish Basin (Vestland Group) (Fjellanger et al.,1996).

The Vestland Group spans the Bajocian-Volgian and is divided into five formations: The Sleipner, Hugin, Bryne, Sandnes and Ula formations, they are capped in the southern Viking Graben by the Viking Group, in the Central Graben by the Tyne Group, and the Boknefjord Group in the Norwegian-Danish Basin (Figure 4.2 & 4.3).

The Sleipner and Hugin formations are found from the southern Viking Graben to the north of the Jaeren High. The Bryne Formation is found in the Central Graben and Norwegian-Danish Basin. The Ula Formation is found from the western margin of the Sorvestlandet High. The Vestland Group can vary in thickness between 120 to 450 m according to wells, while seismic data shows the Group can be found with greater thickness in syn-sedimentary basins related to halokinesis.

The Sleipner Formation is a continental fluviodeltaic coaly sequence. Spanning the Bajocian-Bathonian, it can locally be as young as Callovian (15/12-1). It lies unconformably on relicts of lower Jurassic strata, or even older. Its upper boundary can transition to the Viking Group or the overlying Hugin Formation. The Hugin Formation spans the Bathonian-early Oxfordian and mainly represents a near-shore shallow marine sandstone with occasional influence of continental fluvio-deltaic conditions. Upper boundary transitions into the silt and mudstones of the Viking Group. Deposition in the Sleipner and Hugin formations was related to the transgression of the South Viking Graben and associated retreat of the Bryne Delta (Folkestad and Satur, 2008). In the areas of the Ling Depression and Egersund Basin studied in this chapter, the end of the southerly extent of the Hugin Formation is found interfingering with the continental Sleipner Formation and marine deposits of the Heather or Draupne formations (Kieft et al., 2010).

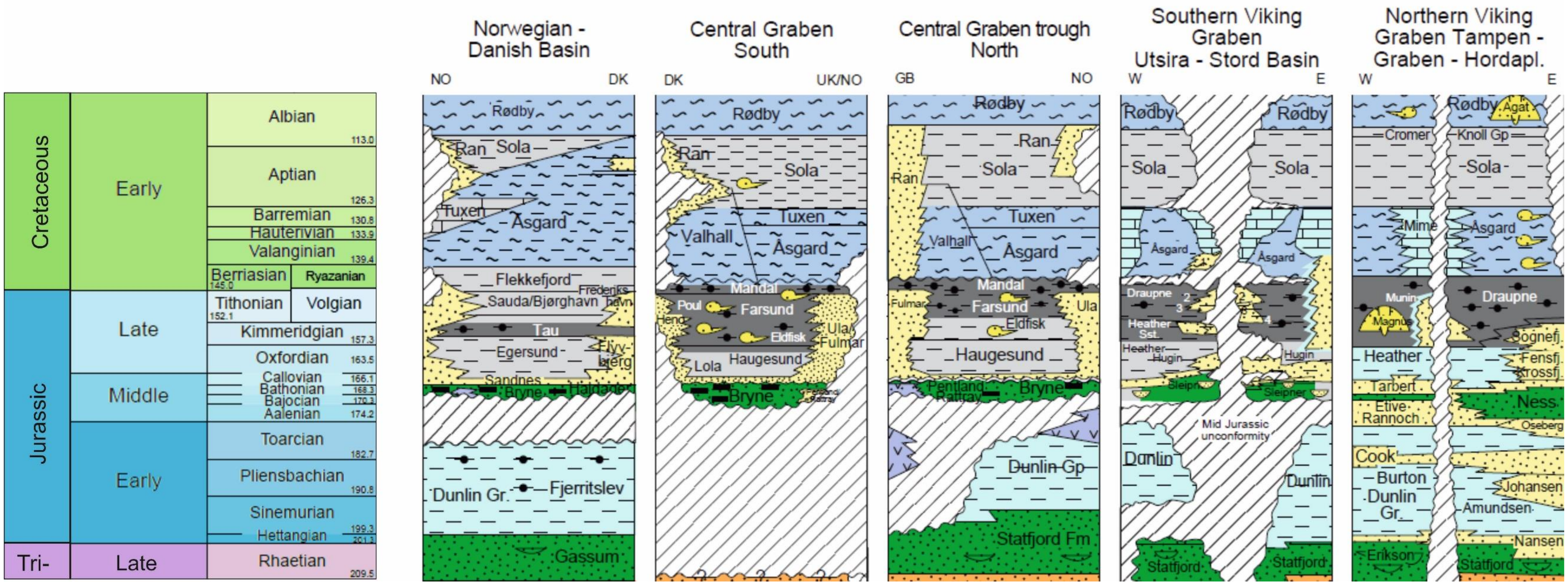


Figure 4.2: Cross-border stratigraphy of the North Sea from Late Triassic to Early Cretaceous. Adapted from the Standard Lithostratigraphic Chart offshore Norway (2017).

The Bryne Formation, spanning the Bajocian-Bathonian, is found further south in the Central Graben and Norwegian-Danish basin. It represents a fluvio-deltaic environment. Comprising non-marine sands interbedded with silt, shale and coal, some shallow marine deposits may have prevailed in fault controlled sub-basins. It is time-equivalent to the Sleipner Formation (Figure 4.2). It is often unconformably overlain by the Sandnes Formation or the Boknefjord Group. The Sandnes Formation was accumulated in the Callovian within the Asta Graben and Egersund Basin - it represents a coastal/shallow marine environment and it is homotaxial with the Hugin Formation in the southern Viking Graben (Figure 4.2). It is overlain by the mudstones of the Boknefjord Group where it is found. The Bryne and Sandnes formations are predominantly sourced from elevated areas in the south and east, e.g. The Stavanger Platform and the Norwegian Mainland (Mannie et al., 2014), with deposition of the early Bryne Formation starting in the Egersund Basin prior the Bathonian-Oxfordian flooding of the North Sea basin (Halland et al., 2011).

The Ula Formation spans the Oxfordian-Ryazanian and represents a shallow marine deposit. It developed around the eastern flanking highs of the Central Graben, changing basinwards (westwards) into marine shales, though it is often recognised as a very thin sandstone. The base of the Ula Formation usually occurs where the marine sandstones change downwards into the non-marine Bryne Formation. The top of Ula Formation gives way to the mudstones of the Tyne Group (Figure 4.3).

In the Central Graben, sequences of lowermost upper Jurassic sequences where drilled are proved to be Oxfordian to early Volgian in age. According to seismic data, they are mainly uniform in thickness and deposited in fault blocks and other structural lows (Gowers et al., 1993). In deep basins, such as the Feda Graben, correlating between individual fault blocks is impossible due to lack of well control and diagnostic features in seismic data (Gowers et al., 1993). Well control does show, however, that over 110 m thick strata were deposited in the Feda Graben during this phase, suggesting that tectonic subsidence was marked and the geometry of the lowermost upper Jurassic sequences across fault blocks is a result of symmetrical subsidence with little interference of fault-block rotation or salt movement (Figure 4.4). The dominant shale lithology of the sequences penetrated by wells also shows that local erosional products were minimal and, subsequently, footwall uplift was not extensive (Gowers et al., 1993).

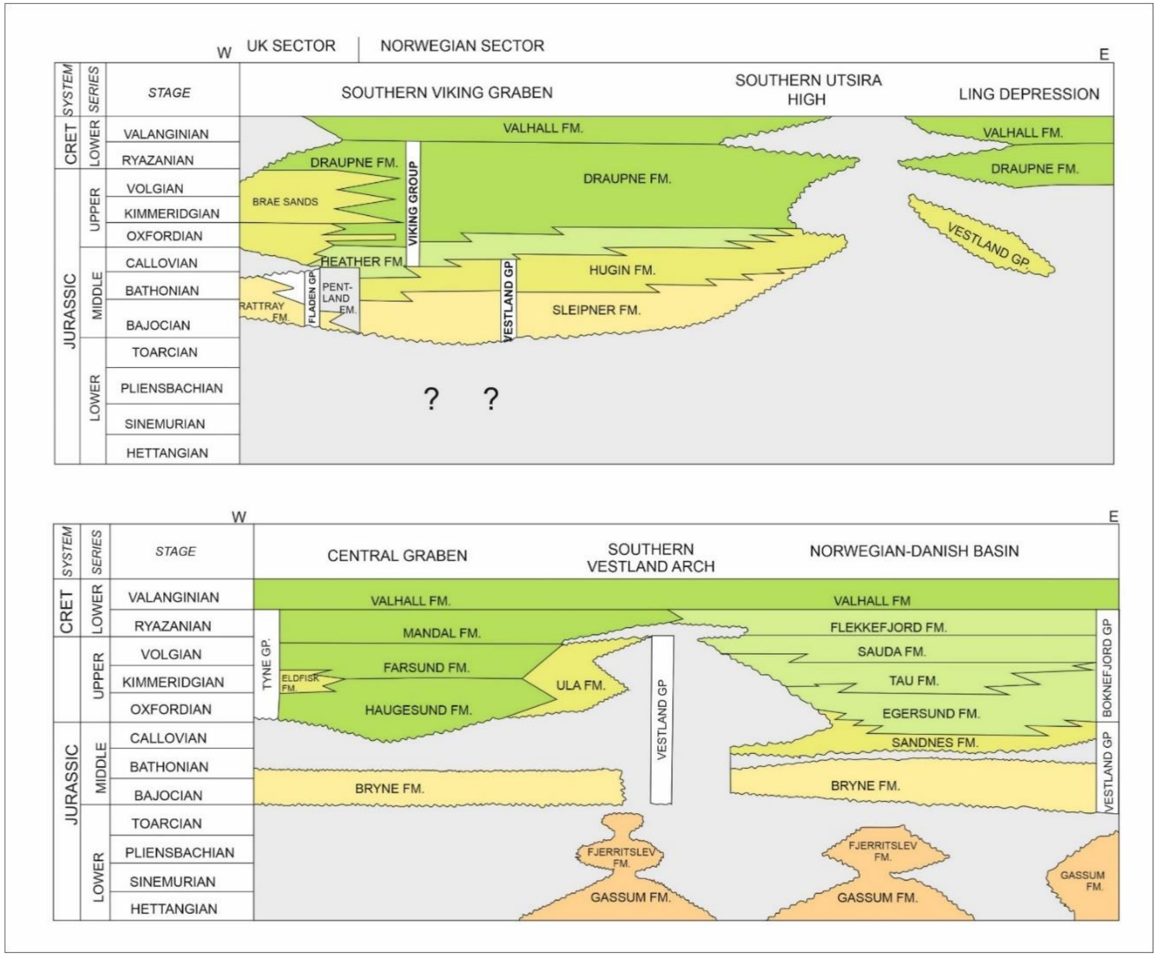


Figure 4.3: Diagram summarising the Jurassic lithostratigraphic nomenclature across the Norwegian North Sea. Re-drawn from Vollset and Doré (1984).

Overlying the Vestland Group is the Upper Jurassic Viking Group (South Viking Graben), the Boknefjord Group (Norwegian-Danish Basin) and Tyne Group (Central Graben).

The Viking Group spans the Bathonian to Ryazanian and is sub-divided into five formations, the Heather, Draupne, Krossfjord, Fensfjord and Sognefjord formations (Figure 4.2). The Heather and Draupne formations are found ubiquitous in the study area and are made up of silt- and mudstone. The Heather Formation spans the Bathonian-Kimmeridgian, representing deposition in an open marine environment. It is overlain by the Oxfordian-Ryazanian Draupne Formation, which has a diachronous contact with the Heather Dormation in basinal areas. It is typically described as a dark mud/claystone deposited in a marine environment with likely restricted bottom water circulation and anaerobic conditions. A few drilled sandstones have been interpreted as occasional turbidites. It is a time and depositional equivalent to the Kimmeridge Clay and the Tau Formation. The thickness of the Viking group is varied as sediments were deposited on a series of tilted fault blocks, reflecting fault activity pre- and syn-deposition. Drilled thicknesses vary from a few meters up to 1039 m (Halland et al., 2014).

The Boknefjord Group spans the Callovian to Ryazanian, and is dominated by shales. It is divided into the Egersund, Tau, Sauda, and Flekkefjord formations (Halland et al., 2014). The Tau Formation of the Norwegian-Danish basin is a local equivalent to the Draupne Formation, spanning the Kimmeridgian to Early Volgian, but is confined to the type area of the Boknefjord Group. Its boundaries are clear as prominent log breaks from the underlying Egersund Formation. The Egersund Formation spans the Callovian to Kimmeridgian and is found locally at the base of the Boknefjord Group. The Boknefjord Group itself is described as deposited in an open marine low-energy basin environment.

The Tyne Group spans the Callovian to Ryazanian and is sub-divided into four formations, the Haugesund, Eldfisk (found locally), Farsund and Mandal formations. It is found at its thickest in axial areas of the Central Graben where >800 m have been penetrated by wells, thinning locally near intra-basinal highs (Vollset & Dore., 1984).

The Haugesund Formation spans the Callovian-Early Kimmeridgian and is ubiquitous in the Central Graben. It is widely distributed around the flanks of basins and intra-basinal highs. It is predominantly shaley and reflects deposition in marine low-energy basin environments. Thin sands are commonly interbedded with the shales and may represent sporadic turbidity flow sourced from the adjacent shelf, where coarser clastics in the Ula Formation were being deposited. A coarsening upward nature of the sequence in logs reflects an overall regression, which was terminated by a transgression and deposition of shales in the Farsund Formation (Figure 4.2 & 4.3).

The Farsund Formation spans from the Kimmeridgian to the Volgian. The Farsund shales were mainly deposited in low energy marine environment, with gamma-ray log profiles suggesting that the unit represents an initial period of deepening followed by gradual shallowing (Vollset & Dore., 1984). Some parts of the Central Graben reveal thin sand stringers in the lower part of the formation, again representing turbidity flows from adjacent shelf areas, where synchronous sands in the Ula Formation were being deposited. The Mandal Formation, the second equivalent of the Draupne Formation, and the last unit of the Tyne Group, spans the Volgian to Ryazanian. It is described as a carbonaceous claystone, dark in colour, deposited in an anaerobic marine environment with high organic productivity and restricted bottom circulation. The Mandal Formation blankets much of the Central Graben.

In the Central Graben the end of the Jurassic (Volgian) saw a change in tectonic style into northwest-southeast trending rotational tectonics of individual fault blocks, with erosion on the footwalls and walls that dip away from the axis of the Graben. The extensive study by Ge et al. (2017) underscores the critical impact of pre-rift salt tectonics and normal faulting on the structural disposition of the North Sea's stratigraphy during this time (Figure 4.5). This aspect is particularly relevant when considering the large deltaic systems of the Brent and Vestland groups, whose deposition is intricately linked to the structural complexities driven by salt dynamics (Ge et al., 2017).

In the work of Ge et al. (2017), the Central Graben area is divided into; rift margin, rift axis, and the Steinbit Accommodation Zone, each characterised by unique structural elements. The rift margin, for instance, houses the Sørvestlandet High, a structural high that exemplifies the extensive normal faulting activity with significant throws that have shaped the subsurface morphology (Figure 4.5). This is essential to consider when examining the deposition of the Sleipner and Hugin formations, as these structural highs have influenced the depositional environment and sediment supply.

The rift axis (from Ge et al., 2017) is composed of large tilted fault blocks, including notable features like the Hidra High and Feda Graben, which are crucial in understanding the sedimentary architecture of the formations within the Viking and Tyne groups. Evidence of this rotational tectonics is most pronounced on the Hidra High where the largest fault block has been eroded so that upper Cretaceous strata directly rest on Pre-Zechstein units at its apex (well 1/3-5) (Figure 4.4) These blocks, dictated by the throws of the sub-salt faults, have a direct bearing on the distribution of sedimentary facies and hence on the hydrocarbon potential of the region. Net subsidence during this phase was small and resulted in shallow-marine sand deposition of reservoir quality in many areas. The rotational subsidence gave way to regional subsidence by the latest Volgian, submerging most of the study area. As sea levels rose, resulting deposition was condensed and became high in organic matter, blanketing much of the area previously recording strata of the Mandal Formation (Ge at al., 2017).

The intricate interplay between the structural style, syn-rift depositional environments, and the subsequent post-rift sedimentary patterns is a recurring theme in the study by Ge et al. (2017). For instance, the Steinbit Accommodation Zone exhibits a shallow base salt horizon, indicative of a tectonically less intense regime as opposed to the rift margins. This has implications for the depositional characteristics of the Ula Formation and its lateral continuity.

Furthermore, the study highlights the variance in salt and pre-rift seismic units across the North Sea, which can be tied to the depositional environments of the Vestland Group's formations. The thickness variations, as revealed by isochron maps in their work, reflect the degree of salt tectonics affecting the pre-rift succession, ranging from elongate salt walls to isolated salt diapirs. Such variations are important when considering the sediment supply and distribution in the formation of the Brent Group and equivalent systems in the Norwegian-Danish Basin, for example.

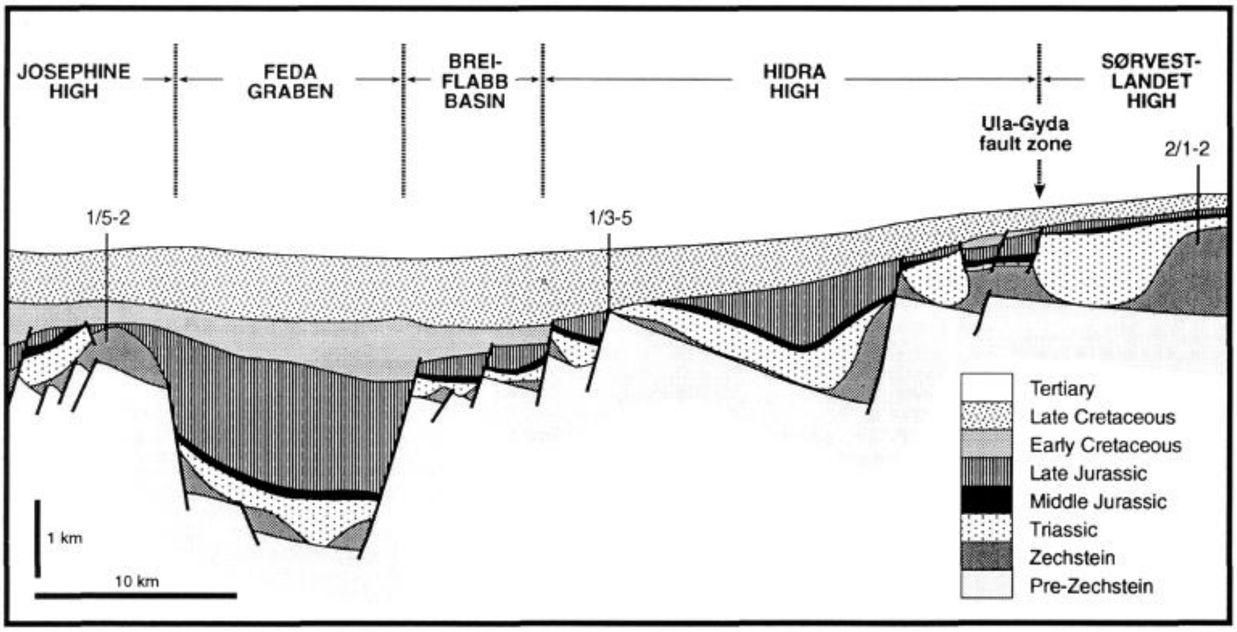
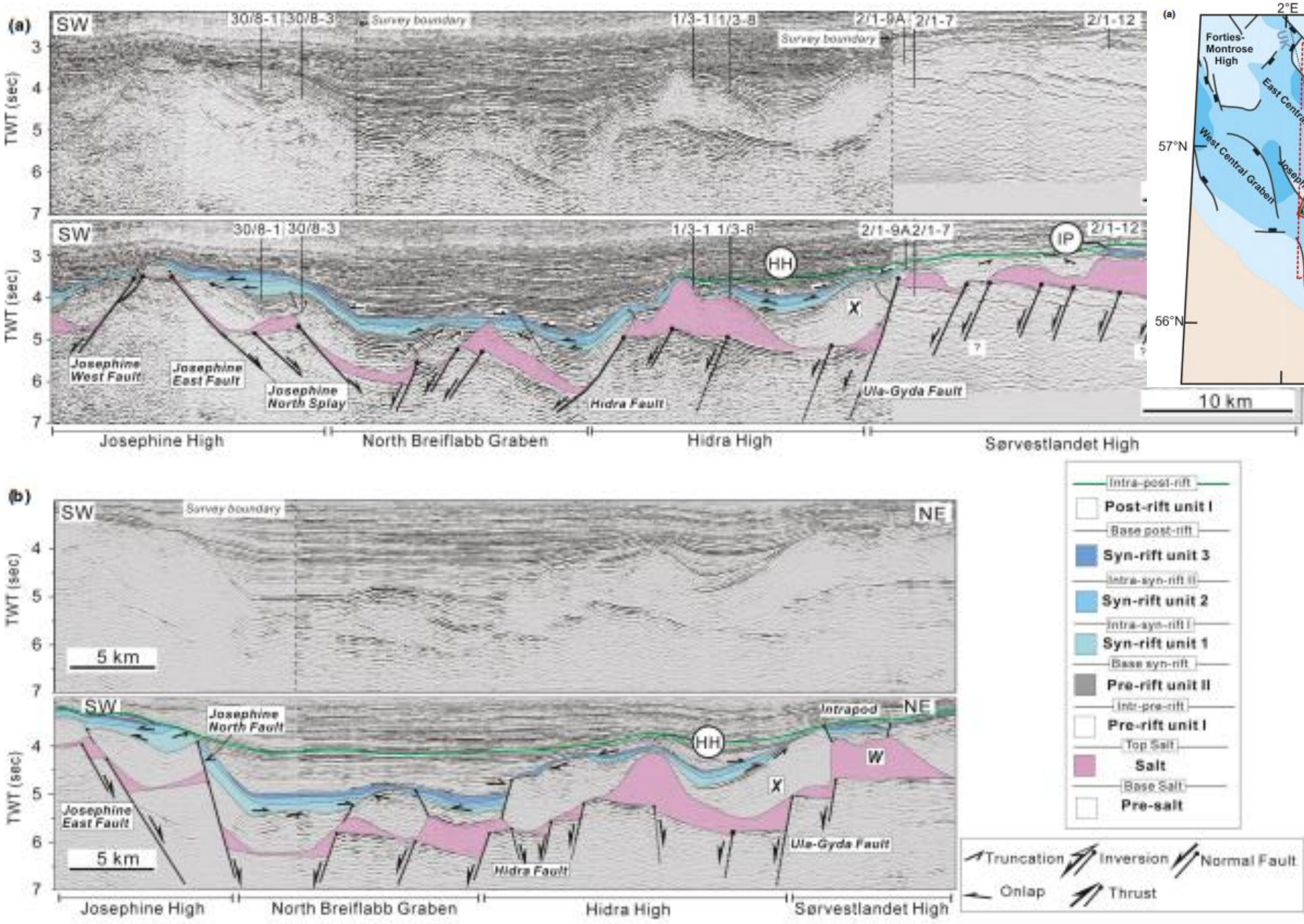


Figure 4.4: Regional cross section illustrating the broad structural styles and sedimentary packages observed from the Josephine to the Sorvestlandet High. Figure is modified from Gowers et al. (1993).

Z. Ge et al.


(a)
SW
30/8-1
30/8-3
Survey boundary
1/3-1
1/3-8
2/1-9A
2/1-7
2/1-12
TWT (sec)
HH
IP
X
Josephine West Fault
Josephine East Fault
Josephine North Splay
Hidra Fault
Ula-Gyda Fault
10 km
Josephine High
North Breiflabb Graben
Hidra High
Sørvestlandet High
(b)
NE
5 km
Josephine North Fault
Josephine East Fault
Intrapod
W
Intra-post-rift
Post-rift unit I
Base post-rift
Syn-rift unit 3
Intra-syn-rift II
Syn-rift unit 2
Intra-syn-rift I
Syn-rift unit 1
Base syn-rift
Pre-rift unit II
Intr-pre-rift
Pre-rift unit I
Top Salt
Salt
Base Salt
Pre-salt
Truncation
Inversion
Normal Fault
Onlap
Thrust

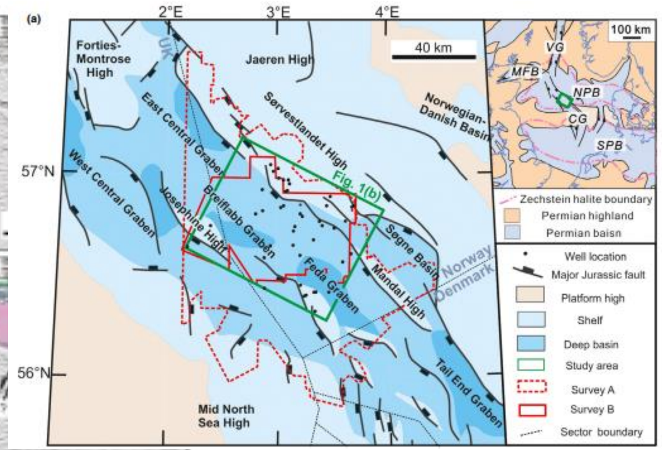

(a)
2°E
3°E
4°E
Forties-Montrose High
Jaeren High
40 km
100 km
Norwegian-Danish Basin
East Central Graben
West Central Graben
Sørvestlandet High
Josephine High
Breiflabb Graben
Feda Graben
Søgne Basin
Mandal High
Tail End Graben
Fig. 1(b)
Norway
Denmark
Mid North Sea High
57°N
56°N
VG
MFB
NPB
CG
SPB
Zechstein halite boundary
Permian highland
Permian baisn
Well location
Major Jurassic fault
Platform high
Shelf
Deep basin
Study area
Survey A
Survey B
Sector boundary

Figure 4.5: Representative seismic sections (above) and interpretation (below) illustrating the structural style and syn-rift depocentre geometry from the northern segment of the Central Graben from Ge et al (2017). (a) E-W section from the Sorvestlandet High to the Josephine High, crossing the Hidra High and North Breiflabb Graben. Note thick pre-rift minibasins and elongate connected salt walls and the contrast between complex sub-salt fault pattern and relatively simple supra-salt faults. (b) NE-SE section across the Sorvestlandet High, Hidra High and North Breiflabb Graben and Josephine High. Note the rotated minibasin (X) and overlying synclinal syn-rift depocentre developed over the Ula-Gyda Fault, and the thick early post-rift succession in the North Breiflabb Graben.(c) Location Map from Ge et al. (2017)showing location of their seismic sections and their study area.

4.4.4 Kerogen characterisation using the Pseudo Van Krevelen Diagram

The Pseudo Van Krevelen Diagram, a graphical representation based on Rock Eval pyrolysis parameters—specifically, the Hydrogen Index (HI) and Oxygen Index (OI)—provides a robust framework for categorizing kerogen types (Figure 4.6). The indices are calculated by normalizing the peaks of select pyrograms (S2 for HI and S3 for OI) against the Total Organic Carbon (TOC). Pyrolysis, the thermal decomposition of organic matter in an inert atmosphere, is employed to evaluate the organic richness, source, and maturity of kerogen (Burnham, 2018).

The characterisation of kerogen types is predicated on their atomic H/C and O/C ratios. Type I kerogen, with a high H/C and a low O/C ratio, originates predominantly from algal sediments, resulting in alginite kerogen that is predominantly oil-prone. Type II kerogen exhibits similar H/C ratios but is derived from marine autochthonous organic matter, including bacteria and phytoplankton, yielding externite kerogen that is both oil and gas-prone due to its heterogeneous composition. In contrast, Type III kerogen, characterized by lower H/C and O/C ratios, is primarily sourced from terrestrial plants, culminating in vitrinite kerogen that is typically gas-prone. Type IV kerogen, referred to as inertinite, is generally associated with coal deposits.

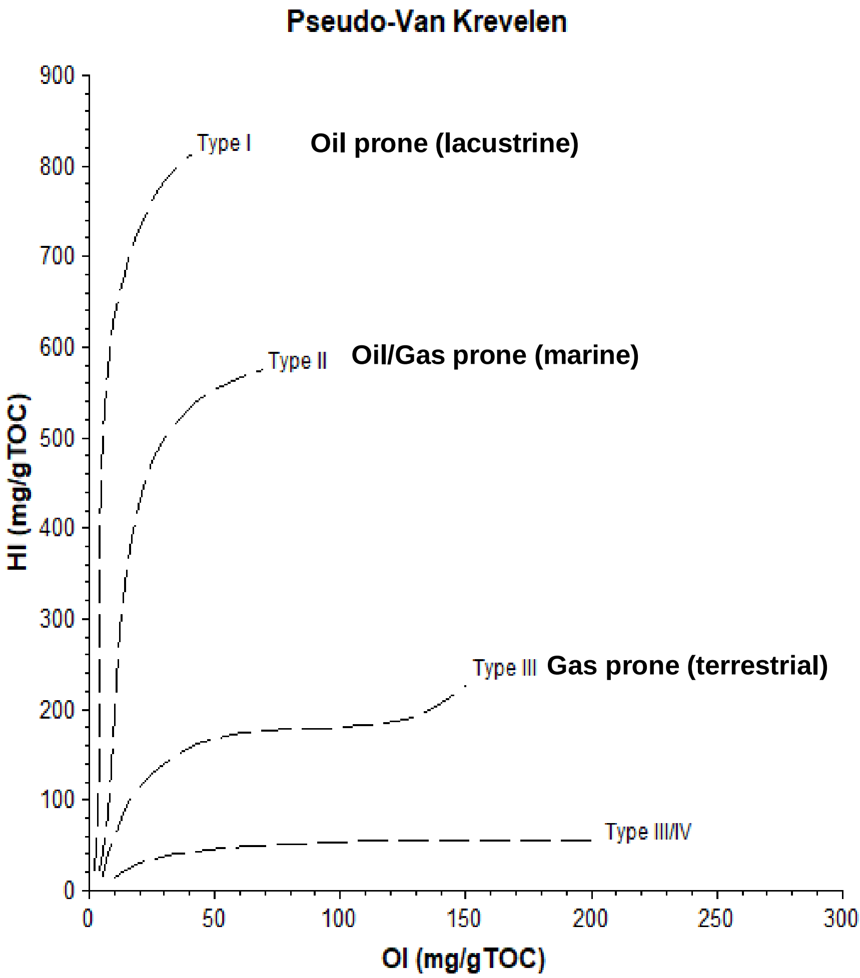


Figure 4.6: Pseudo Van Krevelen Diagram (Author's own) illustrating the cross-plot of the Oxygen Index (OI) against the Hydrogen Index (HI), depicting the typical ranges for Types I, II, and III kerogen.

4.4.5 Biomarkers

Biomarkers, molecular fossils of biological origin, are pivotal in the application of organic chemistry to petroleum exploration. Defined as molecules whose carbon frameworks are unequivocally linked to known biological precursors, biomarkers are the diagenetic heirs of lipids biosynthesized by living organisms (Peters et al., 2005). These compounds, even in minute quantities (ppm/sub-ppm levels), can be discerned amidst a wide variety of other petroleum hydrocarbons through Gas Chromatography/Mass Spectrometry (GCMS) (Weng et al., 2006). Biomarkers not only provide insights into the original sedimentary organic matter and the depositional conditions of the source rock but, due to their resilience against degradation, they also reveal information about oil alteration processes and maturity levels.

Enhanced Characterisation of Source Rocks through Sterane Analysis

Steranes, the diagenetic and catagenetic transformation products of sterols, serve as robust molecular fossils, providing key insights into the thermal maturity and historical biological activity of source rocks. The configuration of sterane isomers, particularly the ratio of 20S to 20R, has been widely recognized as an indicator of thermal maturity, with the ratio increasing as a function of maturation. These geochemical signatures, derived from sterols of eukaryotic origin, are remarkably resistant to biodegradation, making them invaluable for correlational studies between oils and their source rocks.

The chirality of steranes, due to multiple chiral centres, offers a stereochemical narrative of the depositional environment and the evolution of biological precursors over geological timeframes. For instance, specific sterane compounds can signify the salinity of the depositional environment, indicating the prevalence of freshwater or marine conditions (Peters et al., 2005). The C27, C28, and C29 steranes, in particular, shed light on the nature of the organic matter, with algae typically contributing to C27 and C28 steranes, while higher plants contribute to C29 steranes (Figure 4.7). This distribution forms the basis of the Sterane Ternary Plot, which, despite potential overlaps, aids in differentiating the depositional environments of source rocks.

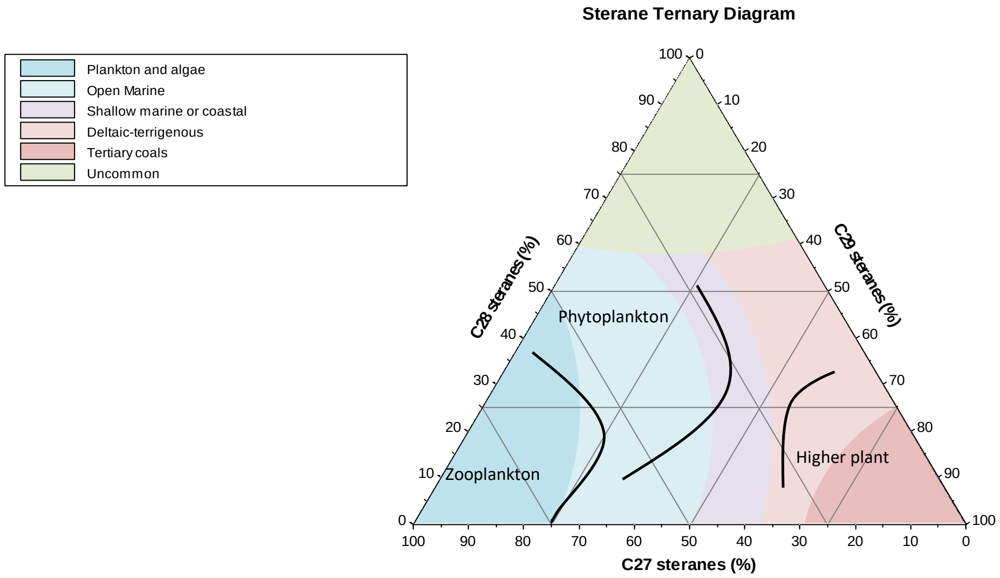
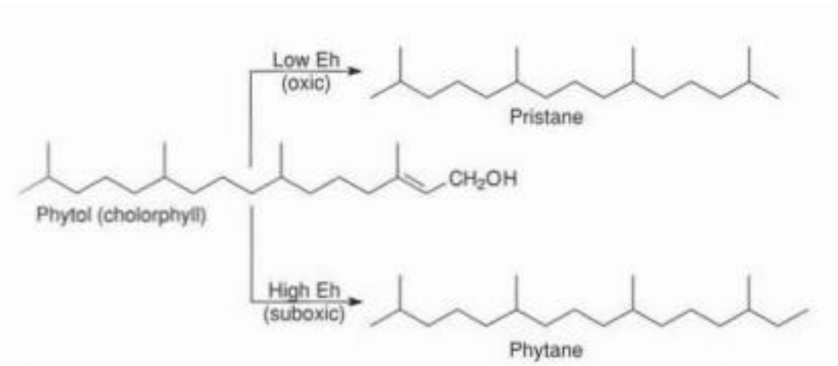


Figure 4.7: Ternary plot (Author's own) of the distributions of C27-, C28-, C29- sterol homologs used to differentiate depositional environments based on the characteristic associations of contributing organisms.

Pristane/Phytane Ratio

The pristane/phytane (Pr/Ph) ratio is a well-established geochemical parameter for inferring the redox conditions of paleoenvironments. Pristane and phytane, acyclic isoprenoid biomarkers, originate from the phytyl side chain of chlorophyll-a and are preserved in sediments and petroleum. The predominance of pristane typically suggests oxic conditions, while phytane dominance implies an anoxic setting. (Figure 4.8). A Pr/Ph ratio below 1 typically suggests an anoxic setting, whereas a ratio above 1 indicates some degree of oxicity (Didyk et al., 1978). Higher ratios therefore, may indicate terrestrial source environments while lower ratios may indicate marine environments (Figure 4.9) Nevertheless, the ratio can be influenced by factors other than depositional environments, such as the maturity of the source rock, which complicates interpretation within the range of 0.6-2.5. Thus, the Pr/Ph ratio, while valuable, should be considered alongside other parameters.

Figure 4.8: Schematic representation of the diagenetic pathways leading to the formation of pristane and phytane from phytol (derived from side chain of chlorophyll), highlighting their relevance in interpreting depositional conditions (Peters et al., 2005).



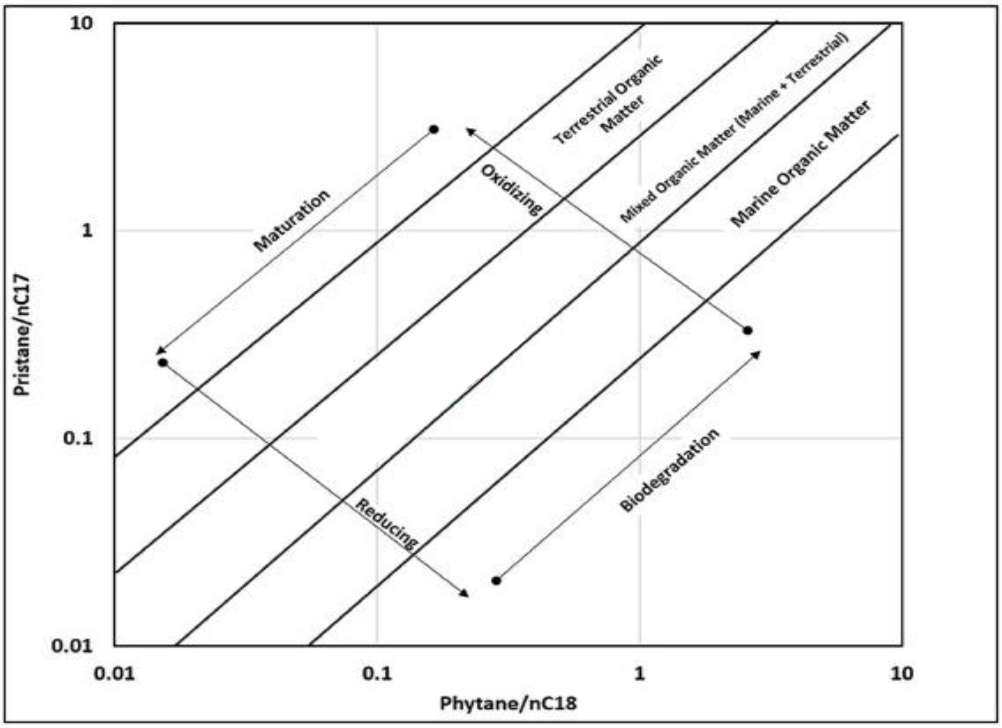


Figure 4.9: Classical Pr/nC17 versus Ph/nC18 plot (Author's own), providing information on depositional environment, kerogen type, and maturity level, where Pristane and Phytane represent isoprenoid hydrocarbons and nC17 and nC18 denote n-alkane hydrocarbons.

4.5 Terrestrial vs. marine organic matter in Middle-Upper Jurassic units in the studied area

4.5.1 Introduction

Kerogen, the insoluble fraction of organic matter in sedimentary rocks, undergoes partial transformation into petroleum through catagenesis, a process influenced by heat and time during burial (Pepper and Corvi, 1995). The character of kerogen is pivotal in petroleum geology, as it serves as an indicator of the type and source of organic matter present in source rocks. This study employs kerogen typology to decipher the diverse organic matter sources in the Upper Jurassic rocks of the Central North Sea within a continental rift setting.

4.5.2 Sources of Organic matter in the system – Kerogen

The Feda Graben, delineated as a deep sub-basin of the Norwegian Central Graben as denoted in NPD Map Figure 4.10, presents a notable kerogen type variability within the Upper Jurassic Tyne Group (Figure 4.11).There is an observable trend in the TOC content, which seems to progressively increase with younger stratigraphic units. The high Hydrogen Index (HI) values in the Mandal Formation correlate with increased TOC levels, contrasting with the lower HI and TOC values in the Haugesund and Farsund formations as shown in Figure 4.11. The kerogen type variability within the rift, particularly in the Feda Graben, indicates a mixed type II/III kerogen in the Haugesund and Farsund formations, spanning from the Callovian through to the Volgian (mid to late Jurassic). This is manifested by the maceral assemblage in the Farsund Formation, which comprises a mix of terrestrial-dominated (vitrinite) and marine-dominated (liptinite) components. The Mandal Formation, spanning the Volgian-Ryazanian, clusters predominantly around type II marine kerogen, signifying the dominance of marine organic matter in the later stages of the Jurassic—a pattern that aligns with observations in the Danish North Sea, where the Mandal Formation is characterised by a more condensed succession with less terrigenous input and dilution, indicative of reduced clastic influx during this period (Price et al., 1993; Back et al., 2011).

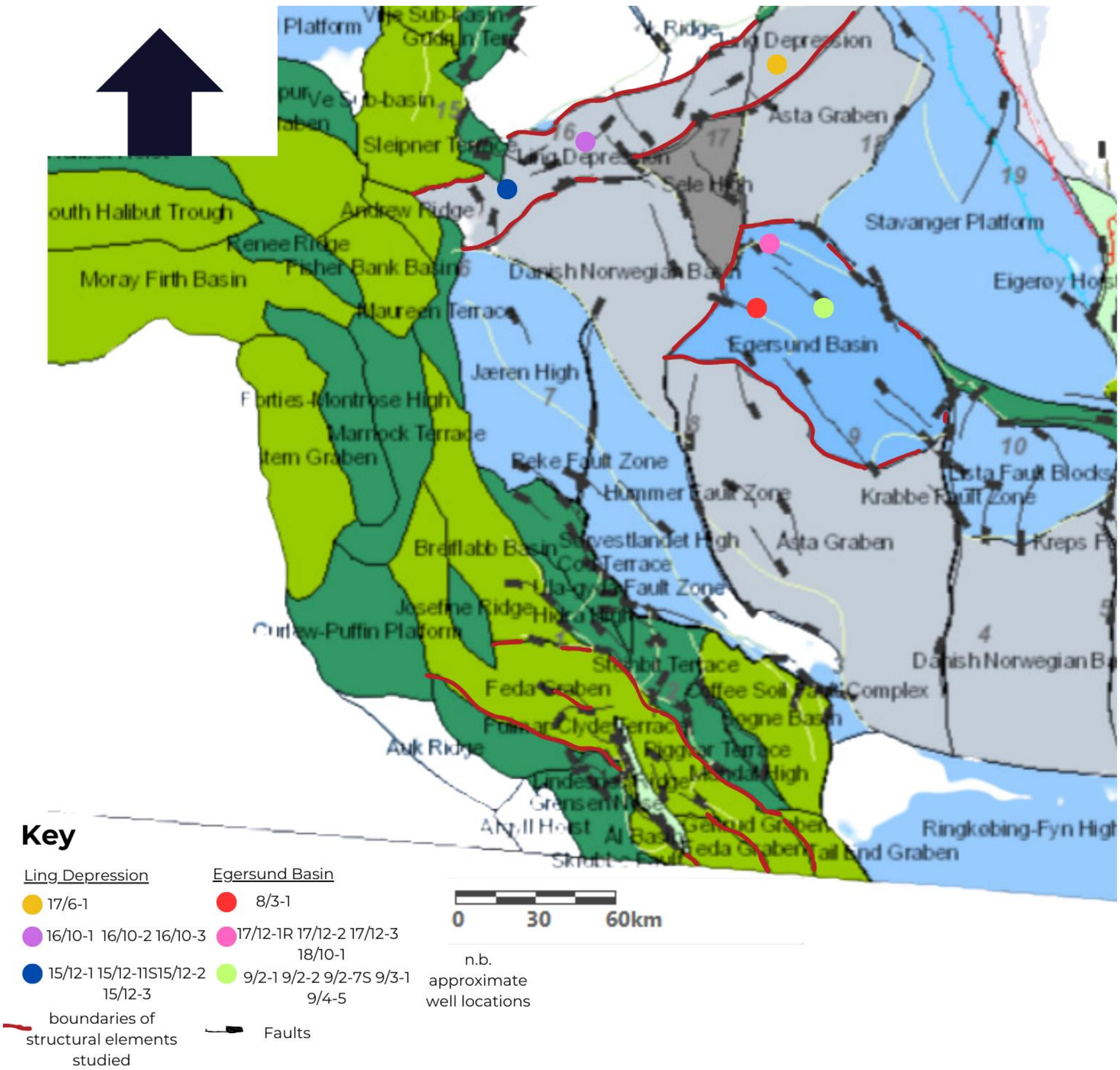


Figure 4.10: Geological Map of the Norwegian Sector of the North Sea delineating various structural elements. The map displays the Ling Depression, Egersund Basin, and Feda Graben as distinguished by red lines. Approximate locations of exploration wells are marked with coloured dots, each labelled with the corresponding well identification numbers. Adapted from Norwegian Petroleum Directorate, 2023. FactMaps [Online]. [Accessed 27 November 2023]

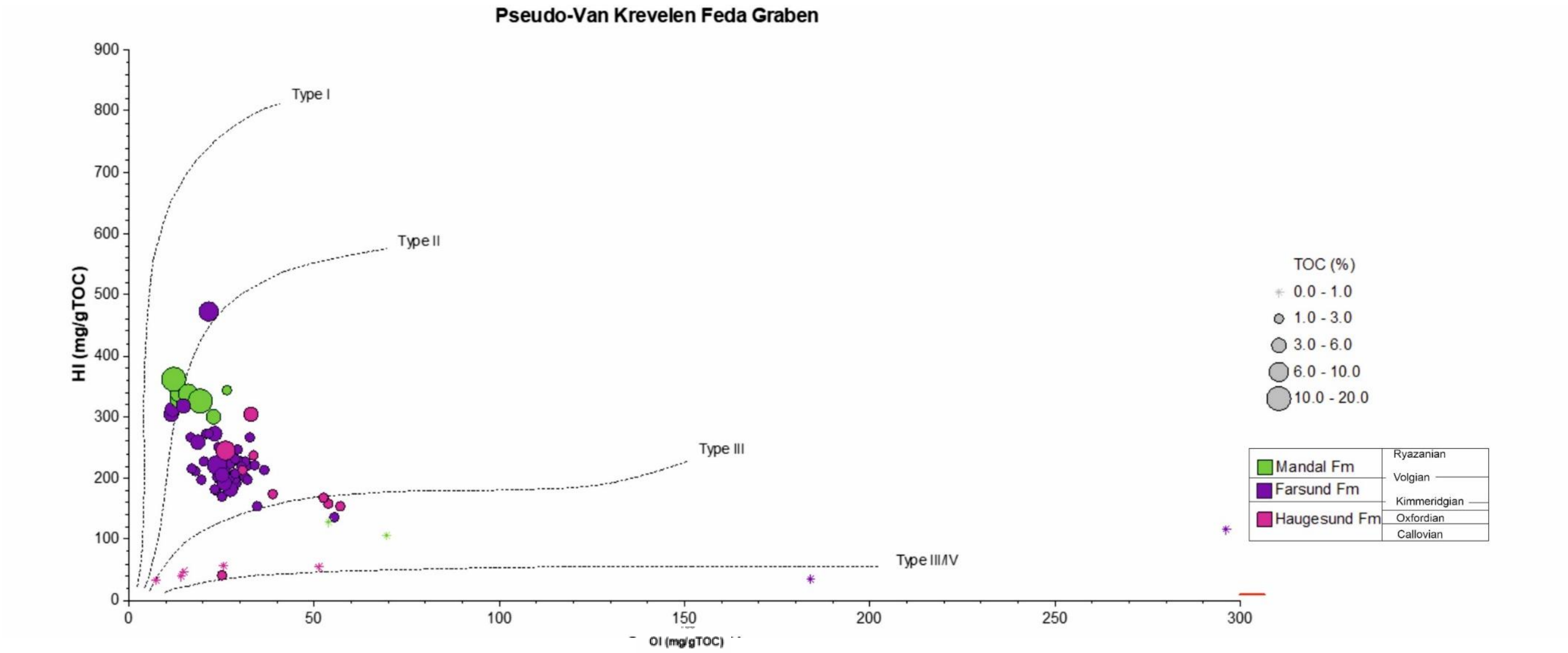


Figure 4.11: Pseudo Van Krevelen diagram for a) the Feda Graben. TOC% and lithostratigraphy are also displayed.

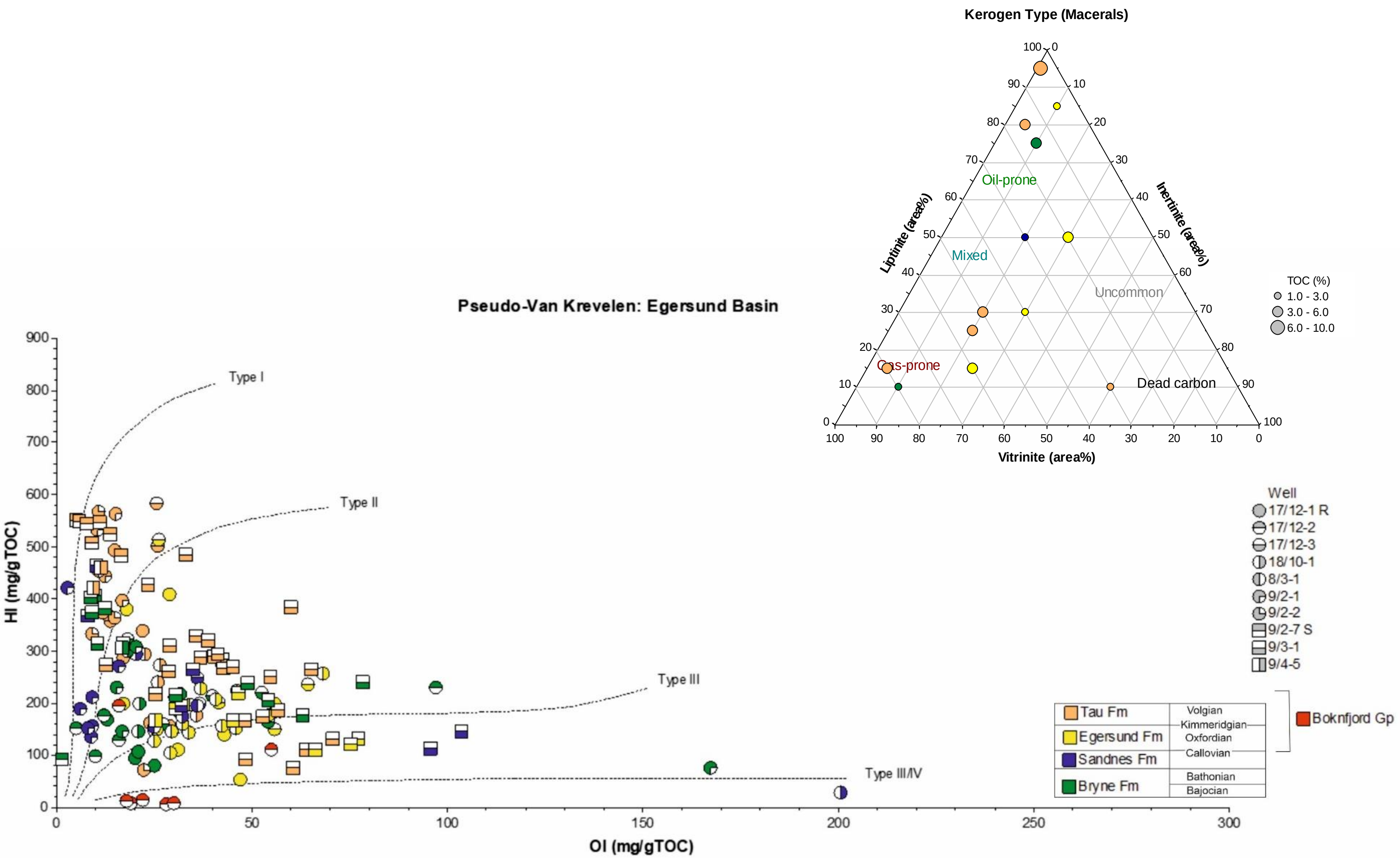


Figure 4.12: Pseudo Van Krevelen diagram for the Egersund Basin. Documented wells and lithostratigraphy are also displayed.

The NE/SW-trending Ling Depression, located in the northern sector of the study area, exhibits kerogen type variability across its formations (see Figure 4.13). Owing to its proximity to the South Viking Graben and the Danish-Norwegian Basin (see Figure 4.10), it features samples from formations belonging to the Viking and Boknefjord Groups, as well as the homotaxial Hugin and Bryne formations of the Vestland Group. Similar to the Egersund Basin (Figure 4.12), the Middle Jurassic Bryne Formation, encountered in the Ling Depression (well 17/6-1 in the east), predominantly exhibits type II marine kerogen, as seen in samples from Figure 4.13. Interestingly, this well lacks significant (and otherwise expected) type III terrestrial kerogen.

For the Egersund and Tau formations, also exclusive to the eastern well 17/6-1 (Figure 4.10 & 4.13), a similar expression of type II marine kerogen is observed. These samples show very little variation and minimal to no type III kerogen contribution, in contrast to those found in the Egersund Basin. In the western wells of the Ling Depression (marked with circle symbols Figure 4.13), greater variation is evident. The Oxfordian-Ryazanian Draupne Formation, occasionally diachronous with the Heather Formation, demonstrates a more marine-dominated variation of kerogen, ranging between types I and II. This variation is indicative of an isolated marine depositional environment. This assertion is consistent with its maceral composition, predominantly featuring marine-dominated liptinite kerogen, and underscores its potential as a prime source rock in the Southern Viking Graben.

Conversely, the earlier Bathonian-Kimmeridgian Heather Formation displays a broad spectrum of kerogen types, ranging from I to III. This diversity likely reflects its varied organic facies history during the rifting phase, with some samples distinctly clustering around type III kerogen. The older Hugin Formation is consistently associated with type III kerogen. Notably, in the Ling Depression, the Hugin Formation is found interfingering with the Heather Formation, suggesting a possible proximity to terrestrial sources in this context.

This could suggest a relatively stable marine depositional environment across the Ling Depression E-W from the Callovian to Volgian . This stability is juxtaposed with the variability observed in the Egersund Basin wells to the south from the same time, which could be indicative of a dynamic depositional environment with variable sediment input. In the Egersund Basin the interplay between the regional extensional forces and episodic magmatic events has dictated the sedimentary infill and, consequently, the organic matter preservation. The variations in biomarker distributions and isotopic compositions across different formations may reflect the juxtaposition of these structural elements, revealing periods of heightened terrestrial influx, punctuated by marine transgressions. These patterns not only align with the seismic stratigraphy indicating fluctuating depositional environments but also mirror the broader tectonic narrative of the North Sea during the Late Jurassic, offering a window into the past hydrocarbon generation mechanisms (Kalani et al., 2020).

In synthesising the data from the Feda Graben, the Ling Depression, and the Egersund Basin, a narrative emerges of temporal shifts in organic matter deposition and kerogen types. These shifts may reflect the evolution of the basins' depositional environments over geological time. The lateral variations observed across the formations and basins provide a foundation for understanding the regional organic geochemistry.

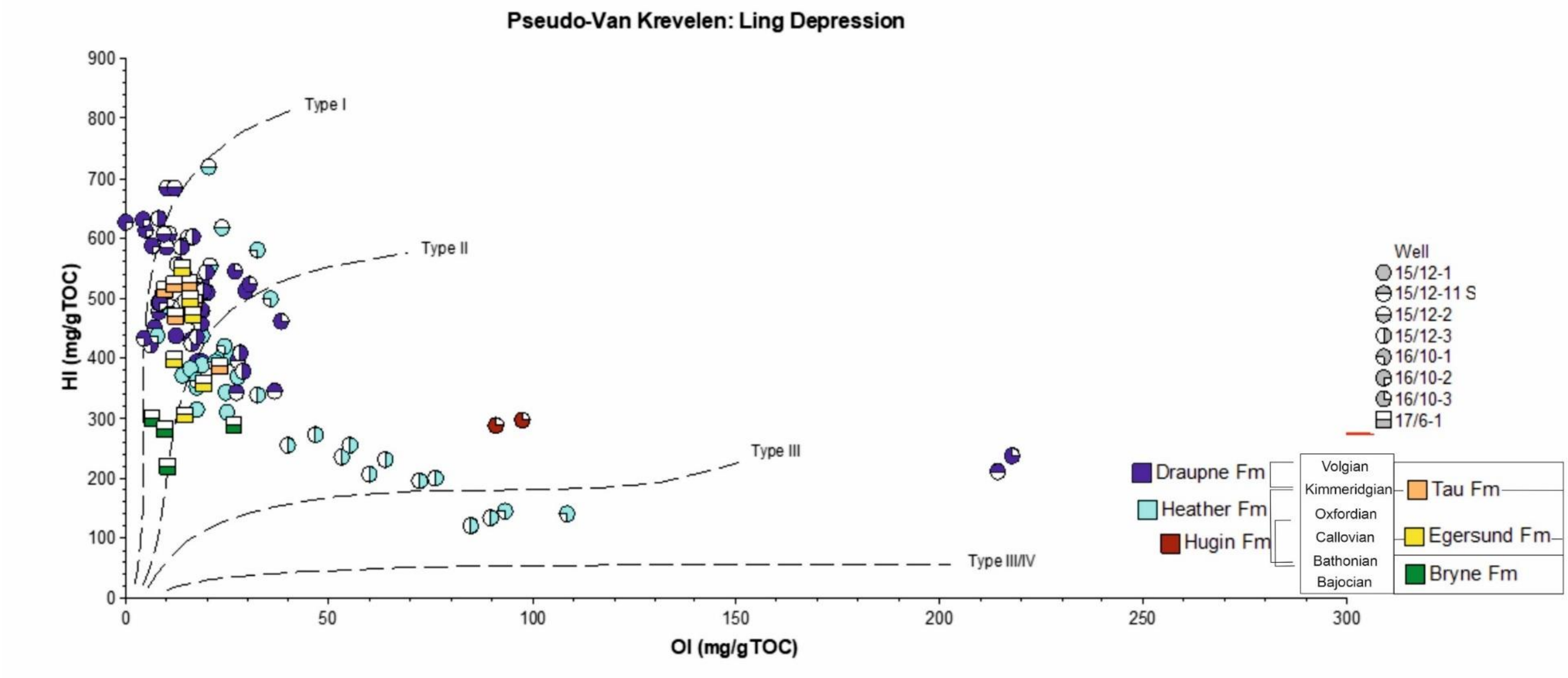


Figure 4.13: Pseudo Van Krevelen diagram the Ling Depression. Documented wells and lithostratigraphy are also displayed.

4.5.3 Key biomarker distribution analysis

The biomarker distribution in the North Sea samples, as reflected in the relative abundance of C27, C28, and C29 steranes, provides a window into the depositional environments of the formations in question (Figure 4.14). The overarching marine or shallow marine/coastal influence is consistent with the overall fundamental structural and tectonic evolution of the North Sea, shaped largely by Late Jurassic-Early Cretaceous rifting events (Peters et al., 2005).

For the Bryne and Hugin formations, however, a notable dominance of C29 steranes is evident, aligning with their sedimentological history as non-marine sandstones and continental fluvio-deltaic influenced shallow marine sandstones. These findings correlate with the established understanding that during the Aalenian transgression, large deltaic systems rich in terrestrial plant material accumulated in the region, particularly in the Brent and Vestland Groups (Fjellanger et al., 1996).

The Ula Formation (Figure 4.14 - pink) is characterised by a sterane composition indicative of a typical shallow marine environment. This mirrors its geological position upon the eastern flanking highs, such as the Sorvestlandet High, and is in harmony with its identification as a shallow marine sandstone within the regional stratigraphic framework (Figure 4.3 & 4.3). The sterane signatures of the Ula Formation thus confirm its palaeoenvironmental setting as delineated by regional lithostratigraphic data.

The Farsund Formation, represented in red on the ternary plots (Figure 4.14b), showcases a variable sterane composition, particularly between samples from the Jaeren and Hidra Highs.

Samples from the Jaeren High, in particular, display a higher C29/C27 ratio, suggesting an increased contribution from terrestrial plant material or a shallower water depth during deposition. This contrasts with samples from the Hidra High, which plot within the open marine depositional area, indicating a more uniform marine OM source. Such spatial variability in biomarker signatures is likely indicative of the differential sediment supply and depositional dynamics at play in discrete structurally controlled elements that are characteristic of the region’s complex geological history, including the rotational tectonics that marked the end of the Jurassic (Volgian) period (Folkestad and Satur, 2008; Kieft et al., 2010).

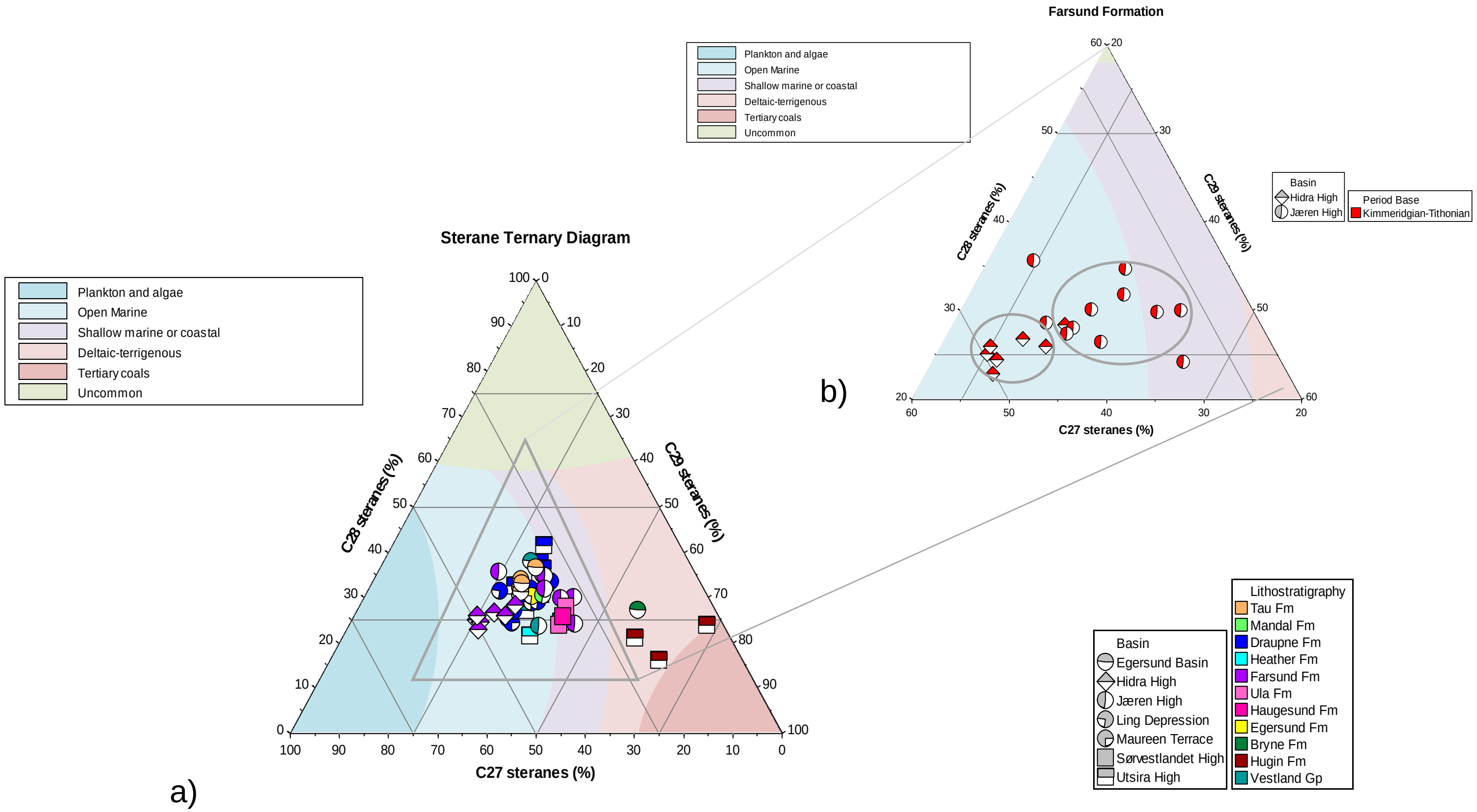


Figure 4.14: a) C27, C28, C29 ternary plot for studied areas by formation and location, b) sterane ternary plot for the Farsund Formation.

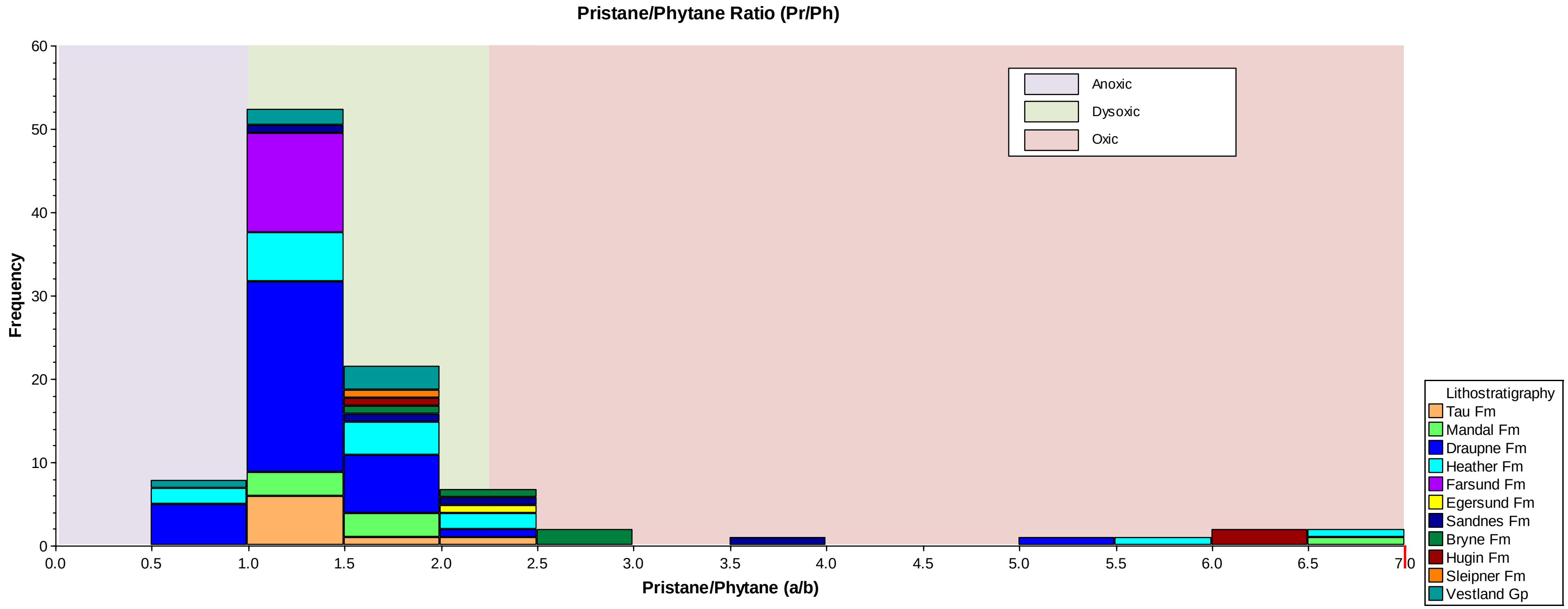


Figure 4.15: Pristane/Phytane ratio of samples inferred that the highest frequency of the source rocks samples were deposited mainly in dysoxic environments, whilst others were likely deposited in anoxic and oxic environments, respectively.

Figure 4.15 presents a histogram of the Pristane/Phytane (Pr/Ph) ratios from the Central Graben formations. Most values fall between 1 and 2, commonly indicative of dysoxic conditions during deposition—a moderate deficiency of oxygen that typically preserves a distinct type of organic matter. Notably, the elevated Pr/Ph ratios, exceeding 3 in the Bryne and Heather formations, align with their coal-bearing lithologies, suggesting a significant terrestrial plant influence. Additionally, marine-influenced formations such as Sandnes and Haugesund, displaying Pr/Ph ratios greater than 2, imply an admixture of terrestrial organic matter, underscoring the complex sedimentary dynamics of the region. Pr/Ph ratios between 0.6 and 2.5 are difficult to interpret with confidence but what can be said is that again the Pr/Ph values are varied, even within formations.

These same samples are displayed in the classic Pr/n-C17 vs Ph/n-C17 diagram (Figure 4.16). This clearly shows that all formations spanning the earliest Sleipner Formation to the latest organic rich units of The Draupne/Tau/Mandal formations show a mixed organic matter source, this is interesting both for later more classically marine sourced rocks to have a clear mixed marine and terrestrial OM signature rather than a distinct marine only source and for earlier middle Jurassic units that are presented as fluvio-deltaic or shallow marine, to have a marine component of organic matter alongside the terrestrial sourced organic matter.

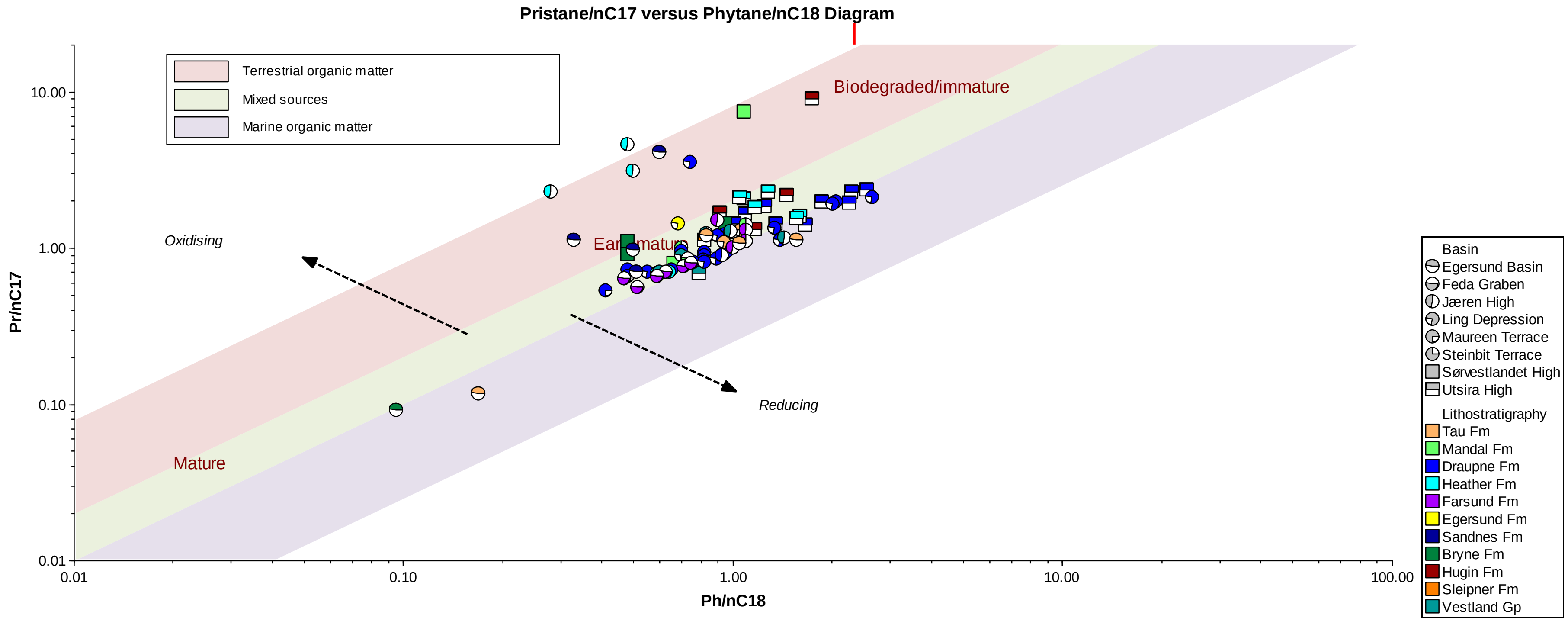


Figure 4.16: Pristane/n-C17 vs Phytane/n-C18 plot of samples in studied area by lithology and basin location (after Hunt 1996).

4.6 Limitations

The present analysis, while insightful, is constrained by the dataset's limitations, and the Author’s analysis and time. This study of the North Sea basin, through its selective analysis of biomarkers and kerogen, has contributed valuable insights into the geochemical signatures of various formations within the Central Graben. While it has undoubtedly broadened our understanding, it is important to critically evaluate the limitations of this work, as they lay the groundwork for future, more expansive research.

One of the study’s primary limitations is the scope of the sample selection. Although the chosen samples were adequate to identify general trends, they may not fully represent the geochemical variability of the entire basin. This limited scope is due in part to the practical constraints of data availability, as the analysis was conducted on an existing dataset rather than on new, systematically collected samples. This pre-selection means that some geochemical nuances, particularly those relevant to localised phenomena, might have been overlooked.

The absence of depth-specific sampling is another limitation, as it prevents a detailed stratigraphic analysis that could reveal vertical trends crucial for understanding the evolution of organic matter and diagenetic processes over time. It is recommended that future studies aim for a more comprehensive dataset, including depth-stratified sampling, to enable a detailed understanding of the vertical geochemical gradients. Further biomarker analyses would elucidate the depositional environments and thermal maturity of the organic matter more precisely. These enhancements would not only refine the current interpretations but also improve the predictive capability for hydrocarbon exploration within these sub-basins. The study's reliance on Pristane/Phytane ratios and Pr/n-C17 vs Ph/n-C18 diagrams to infer depositional environments is a methodologically sound approach, yet it is not without its challenges. These ratios are sensitive to factors such as organic matter maturity, biodegradation, and potentially unrecognized inputs, which could confound interpretations of the depositional conditions. Therefore, while the study has provided a useful broad characterisation, the exact environmental conditions remain somewhat speculative without corroborating evidence from additional proxies.

Looking to the future, this study underscores the need for more comprehensive sampling and standardised analytical methods. Future work could benefit from a larger, more diverse sample set, ideally collected and analysed using consistent, cutting-edge techniques. High-resolution temporal data would further elucidate the timing and duration of depositional events, providing a clearer picture of the basin's geologic history. Moreover, a multi-proxy approach, integrating biomarker data with isotopic studies, trace element analysis, and perhaps paleontological data, could offer a more detailed interpretation of the depositional environment.

4.7 Chapter Specific Conclusions

The geochemical fingerprinting of the Upper Jurassic strata in the Central North Sea has yielded insights that challenge and refine the conventional paradigm of organic matter (OM) deposition in rift environments. Our investigation reveals that terrestrial OM retains a persistent and discernible presence from the early Sleipner Formation through to the later, more organically rich Draupne, Tau, and Mandal formations. This is particularly notable in the Kimmeridgian-Tithonian Farsund Formation, where terrestrial influence is pronounced across the Central Graben area, suggesting a sustained input of terrigenous material even amidst prevailing marine conditions. Such findings underscore the spatial heterogeneity and temporal persistence of terrestrial OM in the sedimentary record, indicating a complex interplay of depositional factors that are intricately tied to the rift's evolution.

The mixed OM signature, manifesting across the aforementioned formations, attests to a dynamic depositional setting where neither terrestrial nor marine sources dominate unilaterally. Instead, there appears to be a continuous, albeit variable, terrestrial influence that persists alongside marine influx. This nuanced depositional narrative is reflective of a multifaceted rift system where local tectonic activity, eustatic sea-level changes, sediment supply dynamics, and perhaps episodic climatic perturbations all contribute to the organic narrative inscribed within the rock record. Similarly, the biomarker compositions corroborate with the depositional narratives derived from the North Sea's lithostratigraphy and tectonics, asserting that the Upper Jurassic strata primarily received organic input from marine phytoplankton with additional contributions from terrestrial higher plants. This interpretation is further supported by the detailed geological context provided, which outlines the interplay of structural complexities, transgressive-regressive cycles, and the influence of deltaic systems on the organic matter distribution within these formations (Peters et al., 2005; Vollset & Dore., 1984; Gowers et al., 1993; Halland et al., 2011; Halland et al., 2014). Our conclusions, are tentative, acknowledging the limitations of the dataset and the scope of study. They serve not as definitive statements but as hypotheses supported by the current evidence, which future research can test and refine. This study contributes to a more nuanced understanding of the variability inherent in rift basin development and serves as a reminder of the complexity of geological processes that can only be fully appreciated through detailed regional studies. The implications of our work are significant, with important nuance for predictive models for source rock potential that recognise that regional geology exerts a profound influence on the geochemical signatures of sedimentary basins, e.g. calibration to account for observed local variances in OM deposition.

5 Discussion

5.1 Early Jurassic palaeogeography of the North Atlantic

Palaeogeographic reconstructions for the North Atlantic Ocean indicate that from the Early Jurassic, and through the rest of the Mesozoic, a combination of marine basins and seaways connected the Tethys region and the Arctic via a North Atlantic rift system (Ziegler, 1982) (Figure 5.1). The Jurassic palaeogeography for the North Atlantic and North Sea areas includes deep shelf, shallow shelf, carbonate platforms and landmasses as main regions. The present study shows that the Lusitanian, Porto and Peniche basins have similar Late Triassic-Jurassic tectono-sedimentary evolutions in the form of a common tripartite stacking patterns, i.e. shared facies associations comprising the deposition of continental strata in the Triassic, evaporite deposits in Hettangian, and fully marine deposits in the Jurassic (Figure 3.3).Such facies associations suggest a co-genetic evolution for the three basins, favouring the interpretation that a seaway existed during the early stages of continental rifting, spanning from the Lusitanian to the Peniche and Porto Basins. This seaway was compartmentalised as early as the Hettangian into a proximal and distal sectors (Figure 3.8).

The predominant depositional setting over the rifting North Atlantic area was one of transgressive pulses associated with rift propagation that started in the Permian (Ziegler, 1988). In the Zechstein Basin of NW Europe, a tripartite stacking pattern of continental-evaporite-marine facies is recorded up to the Mid-Norwegian Sea, although alluvial, lacustrine and other continental facies were once again prevalent in the Triassic due to uplift of the Fennoscandian

Shield in the north, and the Anglo-Brabant and Variscan massifs to the south (Lervik, 2006; Kortekaas et al., 2018).

The Zechstein Sea spanned most of NW Europe but lacked Tethyan involvement. However, from the Late Triassic into the Early Jurassic, rifting propagated westwards from the Tethys Ocean (Ziegler. 1988), part of a North Atlantic rift system largely controlled by Caledonide basement structures (Doré, 1992), and Variscan basement fabric in West Iberia (Pinheiro et al., 1996). The two-sector division of West Iberia documented in this work suggests a marked difference between the proximal parts of the seaway (Lusitanian Basin) and the distal, more developed depocentres that are now part of the Peniche Basin.

A decreasing trend in soluble minerals west of the western periphery of the Tethys Ocean (Jansa et al., 1980), is evidence for the westward propagation of the Tethyan rift and subsequent marine encroachment via inter-continental graben systems. In West Iberia, stratigraphic and compositional similarities exist between the Late Triassic to Hettangian evaporite deposits found in the Lusitanian Basin and Grand Banks in Canada (Wilson et a., 1989; Hiscott et al., 1990; Alves et al., 2003; Uphoff e 2005), signifying the two areas were linked at the time of deposition. By the Sinemurian-Pliensbachian full marine deposition was established south of the Nazaré fault (Stapel et al., 1996). Furthermore, Mouterde et al. (1979; 2007) record mixed ammonite assemblages in the Lower Jurassic of the Lusitanian Basin, where Boreal and Tethyan assemblages were found to co-exist. This demonstrates the influence of both water masses from northern and southern ocean seaways at a time when marine conditions were undoubtedly established off West Iberia.

Further north, seawater incursions followed the axes of rifting from Northern Iberia into the Rockall Trough, Faroe-Shetland Basin, and into a part of a rift arm separating Greenland and

Norway (Ziegler, 1982) (Figure 5.1). This created a connection between the Tethys Ocean and the Boreal Sea through the Viking Corridor by, at latest, Toarcian times (Brikiatis, 2016). With ammonite faunas placing the first connection earlier in the Pliensbachian (Dera et al., 2011), the same transgression resulted in marine deposition with sandy accumulations corresponding to the Dunlin Formation on the margins of basins, but forming the Cook and Johansen formations in Norway and Greenland. This phase brought full marine conditions to the NE Atlantic system as proven by its tide dominated sand deposits (Doré, 1992).

In conclusion, the establishment of a continuous seaway between the Boreal and Tethyan oceans by the Toarcian culminated in the deposition of argillaceous strata across the North Atlantic region (Korte et al., 2015). Ammonite populations in the Sinemurian prove that the Viking Corridor provided a passage between realms where water exchanges occurred continuously, with the magnitudes of such exchanges being controlled by fluctuations in sea levels and currents (Dera et al., 2011). These patterns suggest that a late Pliensbachian sea-level lowstand temporarily segregated populations until full recovery in the Toarcian. A similar setting may have occurred in West Iberia, where outcrop data indicated the first appearance of ammonites in the late Sinemurian (Duarte et al., 2014). According to Skjerven et al. (1983), the likely reason behind the unsuccessful connection between realms in the Viking Corridor prior to the Toarcian was due to deposition keeping pace with the development of accommodation space and rising sea levels throughout the Triassic. We extend this interpretation to the lowermost Jurassic in the south Laurasian Seaway to consider the establishment of a permanent marine seaway to have occurred in the Pliensbachian-Toarcian, following evidence for a first Sinemurian stage of marine incursions in the Lusitanian Basin (Duarte et al., 2014), making our study area similar to the North Sea region (Hesselbo et al., 2007).

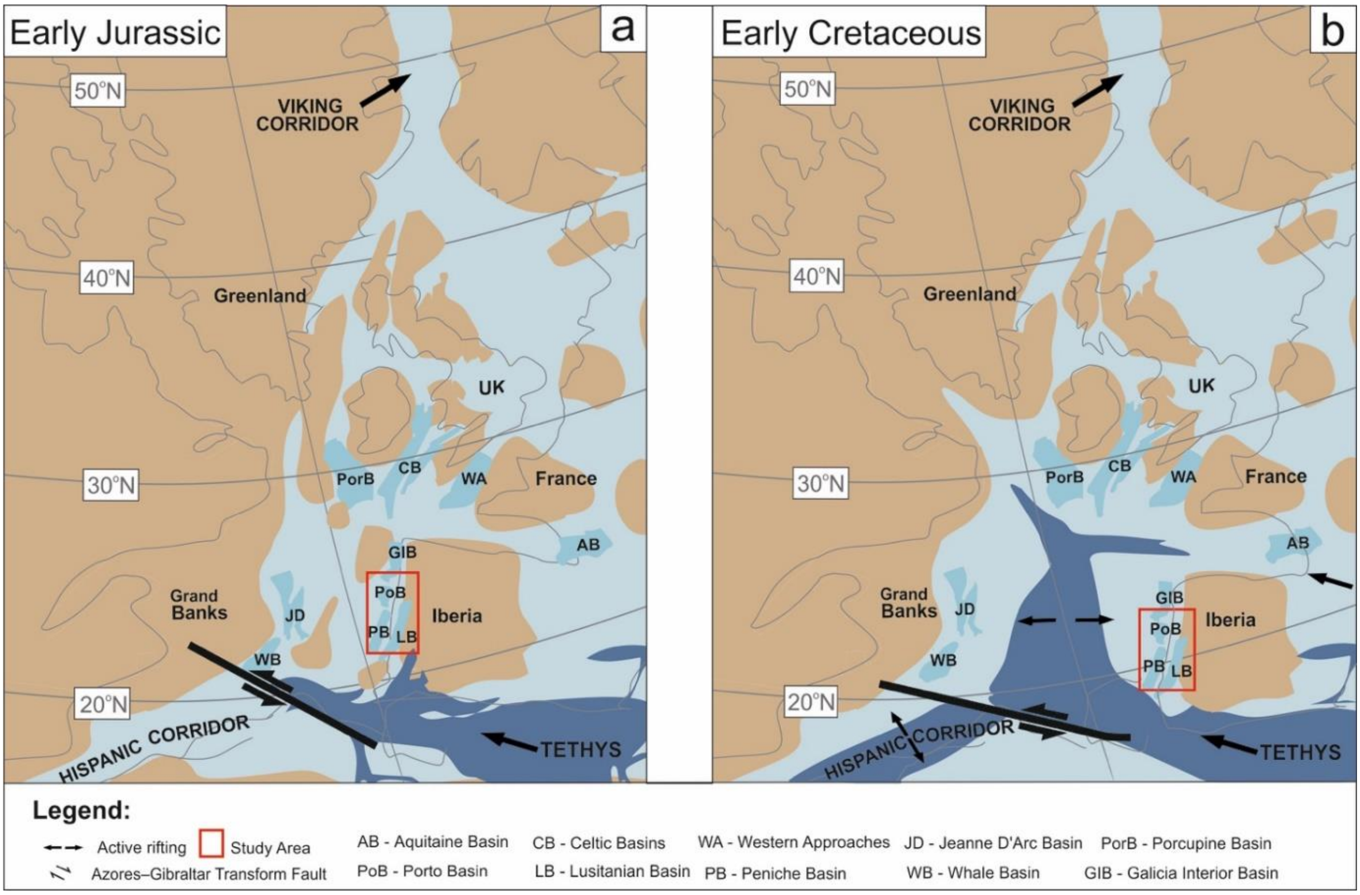


Figure 5.1: Palaeogeographic maps for the North Atlantic Ocean. a) Paleogeography of the North Atlantic during the Early Jurassic highlighting the establishment of several ocean seaways; b) palaeogeography of the North Atlantic during Late Jurassic/Early Cretaceous, when continental rifting broadened the older seaways and led to the rupture of continental crust between Iberia and Canada.

5.2 The role of salt in the evolution of seaways

The geological evolution of the world's oceans has been profoundly influenced by the formation of seaways, particularly those that serve as trans-continental gateways. This thesis introduces the South Laurasian Seaway, an incipient southern extension of the well-documented Laurasian Seaway. Extending over 200 km, it emerged as a response to the Triassic-Jurassic continental rifting in the North Atlantic and is characterised by Mesozoic syn-rift strata spanning the Lusitanian and Peniche basins.

This section aims to classify the South Laurasian Seaway, aligning with the latest research by Rossi et al. (2023) on straits and seaways. Rossi et al. (2023) comprehensive analysis sheds light on marine straits and seaways as crucial connectors of marine and lacustrine systems, offering fresh perspectives on their geological classifications. This thesis seeks to apply these perspectives to the South Laurasian Seaway.

A pertinent question arises in this context: How does the South Laurasian Seaway's characterisation align with the existing geological knowledge of seaway development? According to Rossi et al. (2023), these features exist along a continuum of marine passages, each with unique transitional attributes ranging from a strait through to a seaway, and onto a giant trans-continental seaway like the Laurasian Seaway. Straits and seaways share similar geometric features but differ in spatial and temporal scales. Straits are typically narrower (a few to ~100 km wide) with accelerated marine waters and predictable sedimentation patterns. Seaways are wider (hundreds to ~1000 km) with complex current circulations, housing multiple depositional systems like deltas and estuaries. Geologically, straits are short-term features (thousands to millions of years), forming due to tectonics, volcanic activity, basin collapse, or sea-level changes. Seaways evolve over longer periods (tens of millions of years) due to processes like subsidence, subduction, rifting, and continental breakup. This framework can help contextualise the seaway's role in global geological processes and in elucidating its significance and characteristics as a marine passage during the Early Jurassic..

Work from this thesis reveals thick salt depocenters in the distal parts of the West Iberian margin, bounded to the east by the Slope Fault System and to the west by several seamounts and structural highs, with seismic interpretations indicating depths reaching up to 2500 ms. In more proximal locations of the margin, within the shallower Lusitanian Basin, analysis of industry wells also reveals the presence of upper Triassic-Lower Jurassic salt, albeit with significantly smaller thicknesses. The Slope Fault System distinctly differentiates thick salt to the east and thin salt to the west on the continental shelf. Evidence from seismic interpretation on the continental slope and analysis of industry wells on the continental shelf reveals salt in varying thicknesses spanning several locations. For example, further east in the northern Lusitanian basin, latest Triassic to early Jurassic salt is recorded in multiple exploration wells and at outcrops (Alves et al., 2002), with the bounding to the east at the Porto-Tomar Fault (Pinheiro et al., 1996; Soto et al., 2012).

The South Laurasian seaway of this study is defined, in part, by these thick Triassic-Lower Jurassic salt accumulations. The contrasting thicknesses, up to 2500ms and 850ms across the slope fault system from east to west, reveal that the seaway was divided into two sectors as early as the late Triassic-early Jurassic during the salt deposition period. Their different subsidence histories further corroborate the existence of such a division.

Work from Rowan et al. (2014) on salt basins of passive margins has led to an enhanced set of models that extend beyond the characterisation of pre-rift, syn-rift, and post-rift stages. These models build upon the four-stage model of hyper-extended, magma-poor margins from Peron-Pinvidic and Manatschal, providing clarity in explaining different types of salt basins at passive margins. The character exhibited in the West Iberian Margin is typical of syn-stretching salt deposition, as defined by Rowan (2014), where evaporites are deposited early in the rifting process, resulting in the base salt having original topographic relief and varying in thickness and extent over the margin (Figure 5.2). Rowan describes the West Iberian, and it's conjugate pair, the Newfoundland margins as a type locality for syn-stretching salt, where base-salt relief, the amount of thickness variation, and the presence or absence of salt on footwall highs all depend on the timing of salt deposition within the stretching history. Salt is found in proximal extensional basins such as the Lusitanian and Peniche, and the Whale, Horseshoe, and Jeanne d'Arc basins, but its presence has not been proven in the most distal portions of either margin (e.g. note Figure 3.4) and the disappearance of salt west of the Porto seamount in seismic). The salt deposition here is influenced by existing rift-basin architecture and is concentrated in the more proximal areas of the margin due to its early deposition.

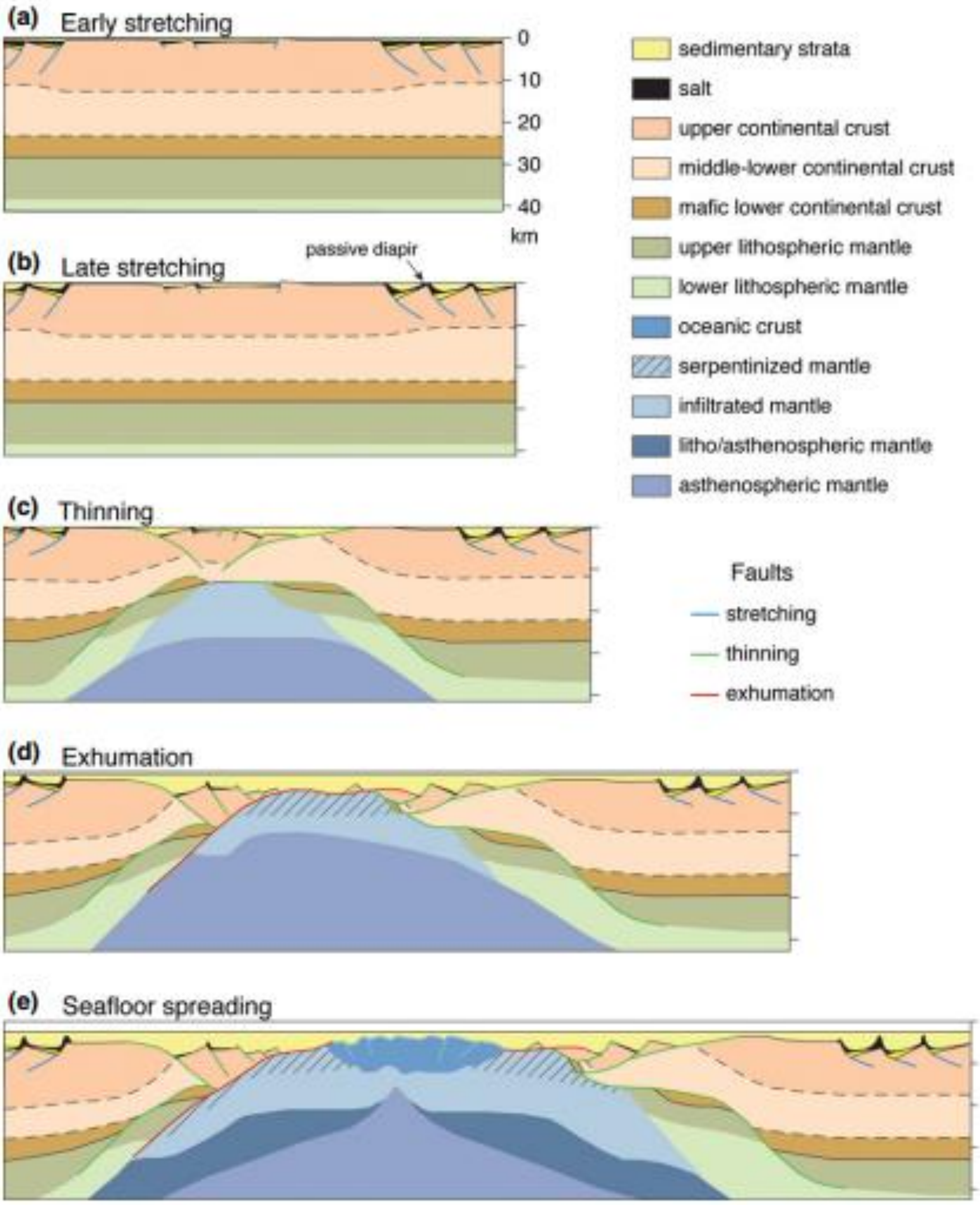


Figure 5.2. Model of syn-stretching salt basin using template modified from Peron-Pividic and Manatschal (2009); a) early stretching stage with salt deposition controlled by active faults; b) late stretching stage with salt diapirism by ongoing thick-skinned extension; c) thinning stage with continued diapirism; d) exhumation stage with only minor continued salt-related deformation; and e) spreading stage showing salt concentrated in proximal areas. From Rowan et al. (2014).

During the Early Jurassic, the North Atlantic recorded a series of ocean seaways as it opened, (Ziegler, 1975) including the trans-continental Laurasian Seaway that connected the Tethys to the Boreal Sea. As discussed in Discussion Chapter 5.3 a tripartite stacking pattern is observed in some key basins and classifying syn-stretching salt within the Iberian South Laurasian Seaway may give further insight into similar North Atlantic Basins, albeit during different times.

In the case of the South Laurasian Seaway, the dynamics of salt movement during the Early Jurassic play a significant role in shaping the seaway's sedimentology and stratigraphy. According to the model from Rowan et al (2014), salt mobility begins during its deposition amid ongoing extensional processes. As long as salt is being deposited, its movement is lateral and downward from basement highs into evolving half-graben structures. This movement is not merely a passive response to tectonic activity but an active part of the seaway's development, influencing sediment distribution and basin evolution. Once non-evaporite strata cover the salt layers, the process of basin isolation concludes, and the overlaying strata are stretched. This stretching leads to reactive diapirism, a phenomenon where salt diapirs break the surface due to the thin nature of the overlying cover. These diapirs grow vertically and widen, causing intervening mini-basins to sink into the underlying salt, dramatically altering the sedimentary environment.

In the work of Fürsich et al. (2020), the Kimmeridgian Alcobaça Formation is studied in the Lusitanian Basin, in an area south of that studied in this thesis, south of the Nazare Fault, analysis of the unit in the sub-basins of the Lusitanian Basin (namely the Consolação Sub-basin and the Bombarral Sub-basin), show it to exist on the 'continental-marine interface'. These sub-basins are separated by the Caldas da Rainha salt Diapir, active since the Early Jurassic. Recent models of salt tectonics and field evidence suggest diapir growth kept pace with sedimentation throughout the Jurassic, with deposition occurring primarily at the diapir flanks, but not on its crest, which was only covered by a thin veneer of roof strata, (e.g. Lopez-Mir et al. 2019, 2020; Davison and Barreto 2020). Fürsich et al.(2020) postulates that, given the model of salt tectonics in the area kept pace with sedimentation, it is reasonable to assume that the Caldas da Rainha Diapir formed a topographic barrier that controlled sedimentation and subsequent sedimentology of the Alcobaça Formation (Figure 5.3). So that, for example, only locally siliciclastic sediments reached the Bombarral Sub-basin in the east whereas other times, marine waters from the Bombarral Sub-basin and the southern Consolação Sub-basin extended westward and northward, respectively, across to the western flank of the diapir. The Alcobaça Formation is therefore, characterised by intricate facies patterns and varied biota, and illustrates the dynamic impact of diapirism on the palaeogeography, facies and organisms of shallow-water basins such as the Lusitanian Basin (Fürsich et al., 2020).

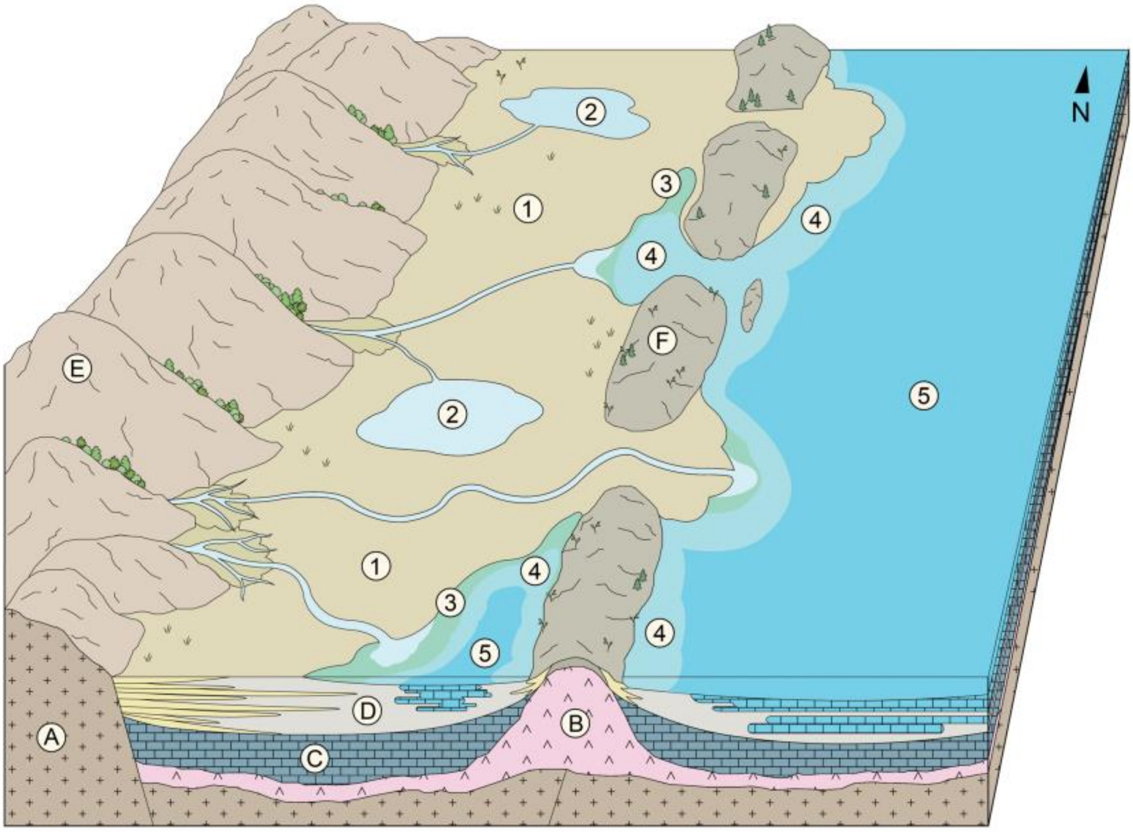


Figure 5.3: Schematic depositional model of the Alcobaça Formation in the Lusitanian sub-basins (northern Consolação Sub-basin and western Bombarral Sub-basin) A: Variscan basement, B latest Triassic/earliest Jurassic salt (Dagorda Fm), C Early Jurassic to Oxfordian carbonate rocks, D Alcobaça Fm, E Berlenge Host Block, F Caldas da Rainha Diapire (emergent passive diapir with several saddles). Depositional/facies: 1: terrestrial, 2: lacustrine, 3: brackish water, 4: marine siliciclastic strata, 5: marine carbonate strata. From Fürsich et al. (2020).

This sheds significant insights into the shallower-portions of the South Laurasian Seaway during the Jurassic. Rift related fault movements and related diapiric movements led to the segregation and segmentation of the seaway, in these proximal areas. Referring back to the work of Rossi et al. (2023) this might more closely align with 'strait-like' conditions in the Lusitanian Basin with diapirism controlling sedimentation on shorter term scales. (Figure 5.4). These conditions are characterised by the dynamic interplay between salt movement and sediment deposition within an active part of a rift system. As salt diapirs rise and deform due to halokinesis, they influence the local topography, leading to the formation of straits and barriers that impact water circulation and sediment transport. This process is integral to the development of marine passages and would have significant implications for the seaway's hydrology and sedimentology. The Kimmeridgian Alcobaça Formation from Fürsich et al. (2020) is proposed as an insightful analogue for adjacent Atlantic marginal basins to utilise the biofacies analysis of the unit as a powerful tool to analyse and disentangle the palaeoenvironmental development of such variable successions in salt rich basins. This may yield important discoveries in the deeper portions of the wider seaway and related basins along the North Atlantic Margin.

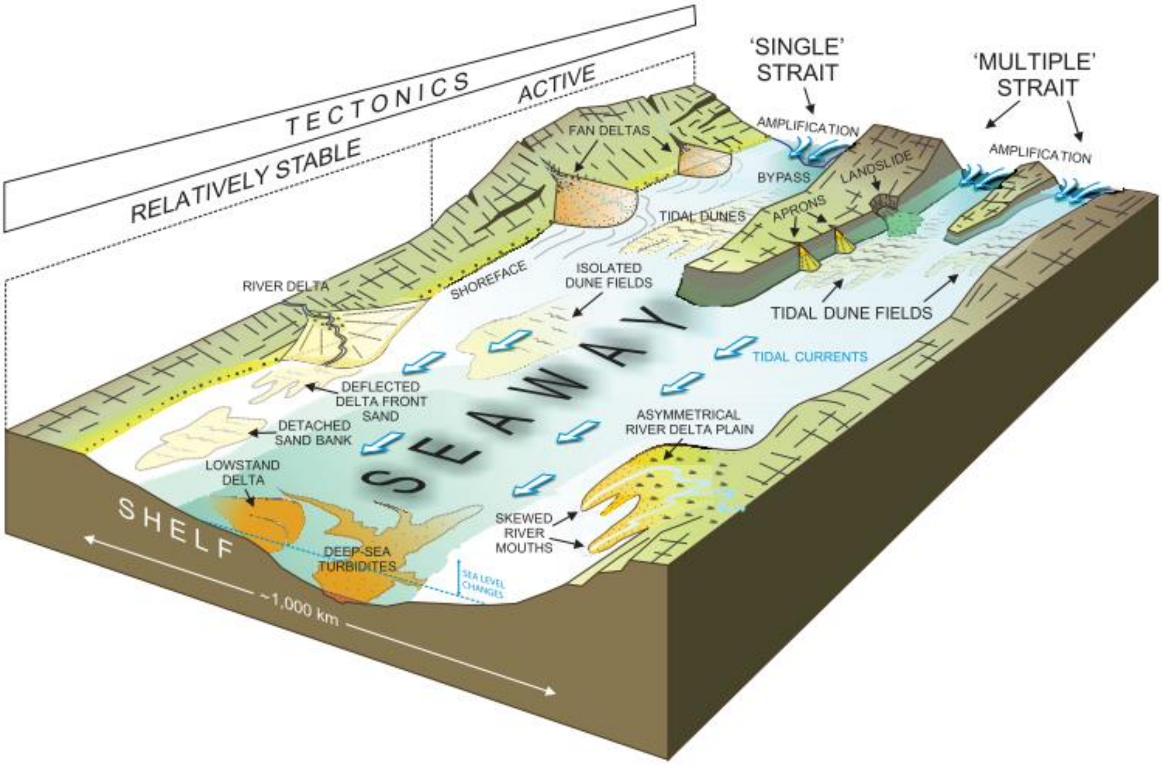


Figure 5.4: Block diagram showing the major spatial difference between straits and seaways. Straits tend to be of the order of kilometres to tens of kilometres (maximum c. 100km) wide passageways, representing individual depositional systems and forming single or multiple corridors. Seaways are wider features (with widths usually of the order of hundred to thousands of kilometres), they may 'contain' straits, as ell as a variety of additional depositional systems. They tend to have wide marginal shelves with prograding coastal wedge. Source: Rossi et al. (2023).

It could be postulated therefore that the South Laurasian seaway depicted in this study comprises of several strait-like marine passages that were connected and dynamic in nature, due to active tectonics and collectively formed a broader more defined seaway through the Late Jurassic that spanned over 200km in width encompassing the Lusitanian and Peniche Basin to form a larger, wider and more substantial seaway as classified by Rossi et al. (2023). The early halokinetic activity in the region, driven by salt movement, would have played a crucial role in this transition. It shaped the seaway's initial configuration and influenced its subsequent geological evolution. As the seaway developed, these early halokinetic processes likely had a profound impact on sediment distribution, biota dispersal, and the overall paleoenvironmental conditions, as it did for the Alcobaça Formation.

The South Laurasian Seaway's evolution from isolated basins to a connected marine passage fits well within the Rossi et al. (2023) framework for seaways, as areas with interconnected rift basins. The salt-driven halokinetic processes were instrumental in ending the basin isolation, soon after it's emplacement, which contributed to subsequent deposition of marine syn-rift strata that significantly influenced the regional paleogeography. This is further supported by the structural and stratigraphic models from Gawthorpe & Leeder (2000). Gawthorpe and Leeder illustrated the manner in which accommodation space and sediment supply, pivotal for the formation of stratigraphic sequences, are controlled by tectonic activities. They elucidated how the variability in tectonic activities, specifically the propagation of normal fault arrays, leads to diverse stratigraphic patterns, reflecting the basin's evolutionary history. Their work emphasised that the architecture of these basins is underpinned by the multifaceted relationship between the 3-dimensional influence of basin interconnections, driven by fault propagation, the changes and maturation of drainage systems and their associated catchments, as well as the effects of fluctuating climatic conditions and variations in sea or lake levels. The phases of

Fault Initiation, Fault Interaction and Linkage, Through-Going Fault, and Fault Death stand out as crucial, serving as the main tectonic drivers that sculpt rift basin architecture outlined in their research. The interconnected Jurassic basins on the Western Iberian Margin are most akin to the architecture of coastal rift related basins during their ‘ Fault Interaction and Linkage stage’ and subsequently ‘Through-going Fault Stage’ where basins such as those in the studied area transition from closed to open rifts, highlighting similarities with the Late Jurassic basins of the North Sea (e.g. Rattey & Haywood, 1993) contextualising the importance of geochemical analyses of these basins in Chapter 4 with direct implications for under explored areas that share a similar evolution.

In this section, the South Laurasian Seaway is presented as a significant geological feature resulting from the Triassic-Jurassic continental rifting in the North Atlantic. Characterised by Mesozoic syn-rift strata, this seaway exemplifies the transition from more narrow straits to more established seaways, as conceptualised in Rossi et al. (2023). Crucially, the study highlights the role of salt-driven halokinetic processes in shaping the seaway's evolution, particularly evident in the West Iberian margin's varied salt deposition. These processes, integral to the seaway's early structural formation, influenced sediment distribution and basin evolution, offering a nuanced understanding of marine passage development. This research not only aligns with contemporary geological paradigms but also provides insights into the complex interplay of geological forces that drive the formation and evolution of significant oceanic seawas, speifically those influenced by salt.

5.3 Tripartite depositional stacking patterns in strata during early North Atlantic rifting

From this work done in this study (Chapter 3.7) exploration wells on the continental shelf of the West Iberia Margin record the significant change in deposition that occurred from the Triassic to the Early Jurassic as the South Laurasian Seaway was developed, as one within a network, providing the gateway between the Boreal and Tethys Oceans. This tripartite stacked pattern of continental, evaporitic and marine strata records the transition between continental to marine deposition with salt deposition as the intermediary facies.

A tripartite stacking pattern appears in other basins associated with the opening of the North Atlantic in the early Mesozoic. One such place is the conjugate margin of West Iberia in Newfoundland, Canada, where the continental deposition of the Eurydice Formation is overlain by the evaporites of the Argo Formation and capped by the marine rocks of the Iroquois Formation (Sinclair, 1995) (Figure 5.5).

The basins of the Irish continental margin also record similar sequences representing the opening of the North Atlantic. Rift-related subsidence occurred during the Triassic in the NE Rockall Basin, leading to the accumulation of extensive red (continental) beds overlain by marginal to marine evaporites and limestones in the Rhaetian, and into the Early Jurassic (Jones and Underhill, 2011). Evaporite deposits are also recorded in the smaller Slyne, Erris and Donegal basins (Tate and Dobson, 1989). In the Porcupine Basin, contemporaneous facies show Triassic strata dominated by sandstone that were capped by evaporite deposits at the end of the Triassic. These are followed by Lower Jurassic marine carbonate and claystone (Jones and Underhill, 2011).

A similar stacking pattern was also recorded in a well drilled 290 km southwest of Lands' End on the UK continental shelf. The Britoil 72/10-1A well in the Western Approaches encountered undifferentiated coarse clastic sediments of sandstone and conglomerates at its base that were correlated to Permian deposits in the southwest of England. These strata are overlain by Late Triassic silty claystone and 600 m of evaporite deposits below claystone of Hettangian age (Bennet et al., 1985).

The Triassic-Early Jurassic rifting episode manifests further east, in the Aquitaine Basin, in the form of thick clastic and evaporite successions. The Aquitaine Basin records Rhaetian to Hettangian argillo-evaporitic sedimentation over the whole basin, expressed in the west as 800-900 m of evaporite with dolomite-anhydrite sequences at the edge and dolomite-anhydrite-halite sequences in the centre of the basin (Curnelle et al., 1982). From the Sinemurian onwards through to the Early Cretaceous, shallow marine sedimentation persisted across the Aquitaine Basin (Curnelle et al., 1982). A similar, but older stacking pattern is also observed in the Zechstein basins of NW Europe. The Southern North Sea and part of the Northern North Sea record a succession of continental rocks (Rotliegend Group) overlain by Zechstein evaporite in the Upper Permian. These are further capped by a sequence of marine rocks. It is therefore proposed that the seaway considered in this work, in West Iberia, may have had a relationship with younger seaways in Northern Europe that also led to the accumulation of tripartite continental-evaporite-marine facies (Figure 5.5). It could be further proposed that the broad region of continental rifting shown in Figure 5.1 was linked to the early Jurassic Viking Corridor, further north, between Greenland and Norway (Figure 2.12).

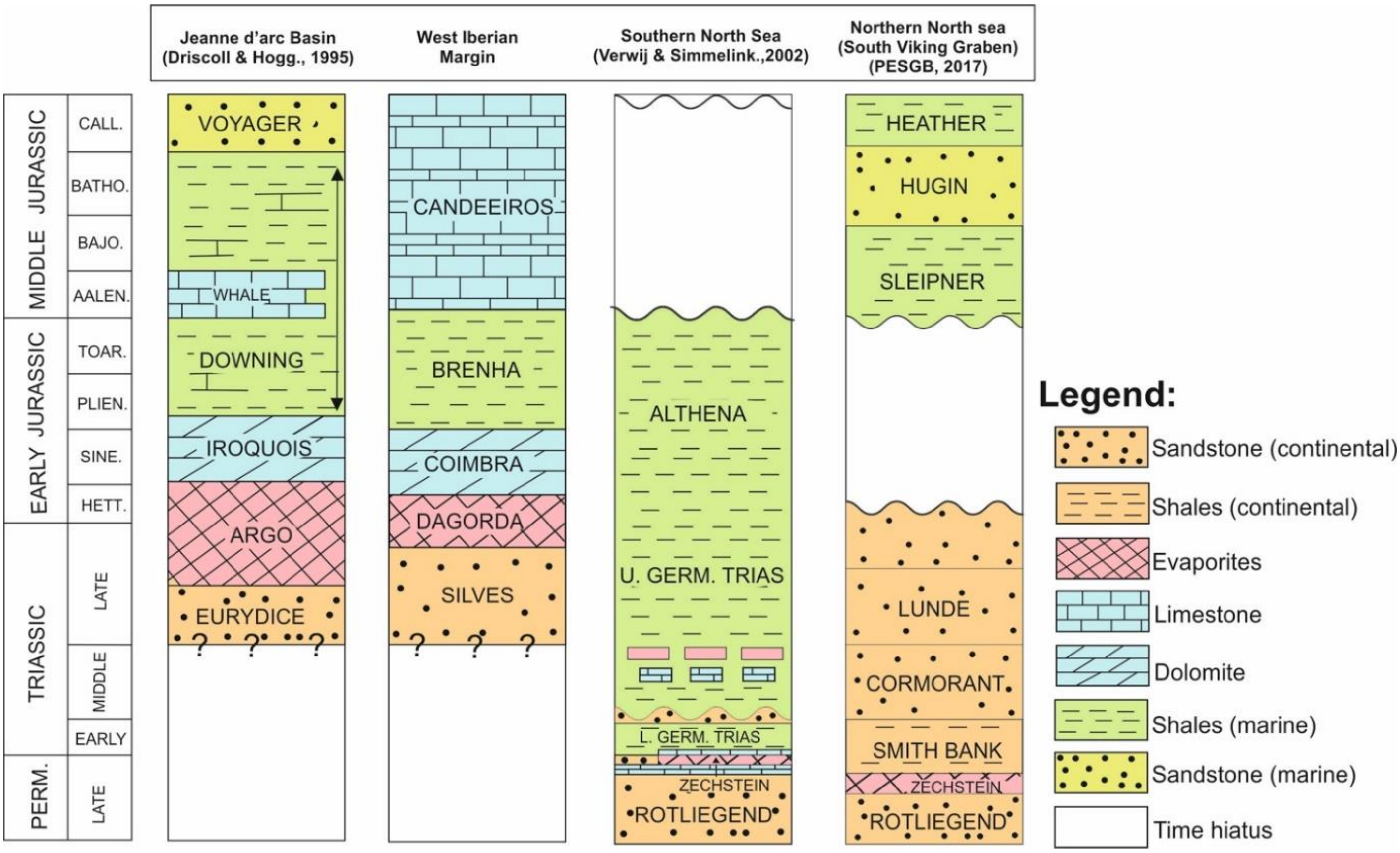


Figure 5.5: Simplified stratigraphic column for the Jeanne d'Arc Basin, West Iberian Margin, Southern North Sea and Northern North Sea revealing similar tripartite stacking patterns during the early stages of continental rifting.

Future research could aim to develop a comprehensive lithofacies and geochemical facies framework building on both the tripartite stacking patterns found in Atlantic Basins and the foundational geochemical work undertaken in this thesis that can be applied to frontier regions in the North Atlantic and other similar geological contexts. An important conclusion to draw from the work in Chapter 4 of this thesis looking at organic matter types in the study area on a base level of kerogen type and few key biomarkers in a failed rift arm of the North Atlantic, is that despite progression of a rift and marine facies sequences being deposited, there is no defined trend of dominating marine organic matter, and/or subsequent diminishing of terrestrial organic matter. In fact there is, in most cases, regardless of age (unit) and area, a supply of terrestrial organic matter entering the system. This is echoed in the important role terrestrial organic matter plays in the detailed ocean seaway/gateway work of Wagner and Pletsch, (1999) and Mutterlose et al., (2003). There is scope therefore for further work on a multi-disciplinary assessment of the study area, to yield more detailed findings of the geochemical nature of the rocks and the influence tectonics played during continental rifting in possible seaway settings.

However, in this case, a broader implication can be drawn to hydrocarbon exploration. As demonstrated in this thesis, similar conditions of continental rifting affected the whole North Atlantic region over the Jurassic, at different times. It is speculated that the dynamic nature of continental rifting, allowed for in varying degrees consistent terrestrial organic matter input into source rock deposition through the upper Jurassic in the study area, likely a result of sea level changes and footwall uplift shedding material into depositional basins. Syn-rift sequences yet undrilled in previous rifting axes in the southern north Atlantic, for example, could therefore present with similar geochemical characteristics. It is during early rifting of oceans that provide an excellent chance of survival of organic matter owing to high sedimentation rates, and possible anoxic conditions of lakes and closed seaways promoting high rates of preserving the organic matter (Cornford, 2005)

With a proposed mixed kerogen type in undrilled similar co-evolution syn rift units it can be said that there is a possibility of oil and gas generation of varying proportions. Work done by (Cedeno et al., 2021) show that varying proportions of kerogen type II and III, as demonstrated by high HI and maceral assemblages is evidence of kerogen heterogeneities. This therefore effects kinetic stability and predicted onset of petroleum generation (Cedeno et al., 2021). Figure (5.6) shows from their work that variability in activation energies results from variation in kerogen (specifically macerals) ultimately resulting in kerogens of a mixed nature having a broader higher range of activation energies compared to those of a more homogenous nature dominated by liptinite (marine) that is lower and narrower.

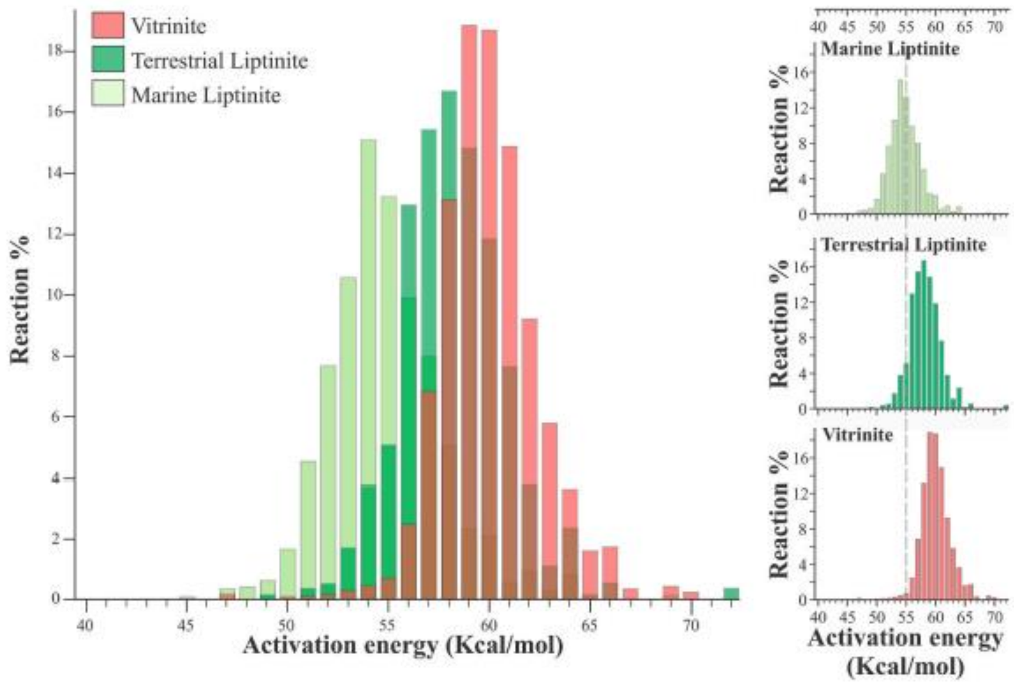


Figure 5.6 Average activation energy distributions computed according to volumetrically predominant kerogen maceral from the study of Cedeno et al. (2021).

6 Limitations

In the geochemical chapter of the thesis (Chapter 4), access to geochemical database in the Norwegian North Sea, was provided and collated by IGI ltd. The wealth of data was vast, and for the purposes of this study several quality check steps were taken on the software pIGI ltd to remove samples that were likely contaminated or not fit for purpose. Steps were taken to leave unstained rocks of mostly, shale and silt composition. During this quality check process, it is likely that some viable or outlier samples have been missed and not considered. Additionally, not all viable samples from the study area contained results of different geochemical parameters and therefore it’s possible that in certain graphs some samples from stratigraphic units are not represented and in others, samples from one unit could be over-represented, resulting in the possibility of some unconscious bias. Aside from the huge advantage of having access to a broad database containing information in many areas, a clear limitation of using this geochemical data is that it was not gathered and processed for this thesis, it is in fact a compilation of results from many different laboratories entered into the IGI database. This information was entered and modified for nomenclature purposes by the IGI team to allow for accurate and more reliable correlation. Caution should always be applied when comparing biomarkers parameters from different laboratories (Mello et al., 1998).

Interpretation of the geochemical data in this thesis, is also only foundational, leaving scope for more detailed work to be done. Kerogen type I-IV classification is only one method of typifying Kerogen, and key findings are made by using macerals and vitrinite reflectance. Additionally, no definitive recognition of kerogen types or depositional environments can be assigned to formations in the study area from the results of Chapter 4. The broad scope of the thesis and time limitations meant that no detailed analysis by depth, well or location was undertaken. This is explained in the chapter specific limitations.

Biomarkers are not exclusive and a compound or set of compounds should be used with caution to support an origin or paleo-environment as there are commonly exceptions and caveats (Peters et al., 2005). Conclusions on correlations, source and depositional environment should always be based on a thorough evaluation of all of the available geochemical information including other biomarkers, supporting isotope data, statistical multivariate discriminate graphs (Peters et al., 2005) combining selected biomarkers and isotope data can effectively discriminate different organic facies. For this reason, biomarker analysis in Chapter 4 is only used for supportive purposes.

A common theme in studies relating to oil and gas using seismic data, is lack of accessible borehole data. Fortunately, the proximal sectors of the west Iberia study in Chapter 3 had sufficient accessible borehole data, interpretation of the distal area relied on extrapolation of these and one distal ODP well and the use of seismic interpretation. This meant through seismic interpretation true lithological identification was impossible. Additionally, due to the nature of seismic data, seismic facies can only suggest a range of possible lithologies in the absence of well control. Correlation from boreholes in proximal areas and previous interpretation in the area were used for the purpose of local lithology and structures, increased quality of seismic resolution in this study meant that base salt could be resolved, a key finding of this work (See Chapter 3 for methodology).

Building of pseudo-wells and subsequent modelling of tectonic subsidence using Schlumberger's PetroMod® 1-D Airy backstripping techniques in these locations relied on the above seismic interpretation. The average palaeobathymetry for the pseudo-well models was constrained by biostratigraphic and lithological data from Lu-1 (before Cretaceous) and DSDP Site 398 (Cretaceous–Cainozoic) (Figures 3.2 and 3.3). The backstripping calculations (interpreted palaeobathymetry for the pseudo-well models) are largely constrained by DSDP Site 398 down to the Barremian, below which level assumptions were made that Jurassic palaeo-water depths in the offshore locations were greater than those calculated from the Lu-1 (see Supplementary Table 1 for an example of input parameters in a pseudo-well model). Rapid increase of palaeowater depth during the Late Jurassic-Early Cretaceous was also accounted for as a result of advanced rifting leading to continental breakup (e.g. Alves and Cunha, 2018).

7 Conclusions

The conclusions of this thesis are:

- Triassic–Early Jurassic continental rifting in the North Atlantic led to the establishment of a ~200 km wide seaway in West Iberia.
- The thickness of the West Iberian salt has been quantified for the first time, varying from 1.7 km to 2.5 km in the main depocentres of continental-slope basins. This, and an overlying thick succession of Lower-Middle Jurassic strata, indicate the presence of a South Laurasian seaway relatively wide and extending into what are, at present, continental-slope basins.
- The marked Early Jurassic subsidence observed in the in the salt-rich depocentre reaches over 2000 m by the Hettangian and contrasts with the results from exploration wells drilled on the continental shelf. These more proximal wells recorded a maximum of 800 m of subsidence at this time, a character emphasising how partitioned this seaway was.
- Continued tectonic subsidence throughout the Early Jurassic is estimated based on tectonic subsidence models, recording a maximum of 5 km in the offshore Peniche Basin. This value compares with the 1.1 km in the proximal Lusitanian Basin.
- Tripartite continental, evaporite and marine facies associations spanning the Late Triassic to Early Jurassic in West Iberia, record the development of the seaway in this location, the south Laurasian Seaway.

- The geochemical fingerprinting of the Upper Jurassic strata in the Central North Sea reveals a consistent presence of terrestrial organic matter (OM) throughout various formations, challenging traditional views of OM deposition in rift environments. Notably, in the Kimmeridgian-Tithonian Farsund Formation, there is a pronounced terrestrial influence, indicating a complex depositional interplay and a sustained input of terrigenous material in a predominantly marine setting.
- The mixed terrestrial and marine OM signature across the Upper Jurassic strata reflects a dynamic depositional environment influenced by local tectonics, sea-level changes, sediment dynamics, and potential climatic variations. This nuanced understanding highlights the geological complexity in rift basins and emphasises the need for detailed regional studies. The findings have significant implications for predictive models in resource exploration, suggesting a need to account for regional geological variances in OM deposition.

8 Appendix

Supplementary Table 1: Data table with input parameters of Pseudo-Well 1 from Petromod 1D. This table serves as an example of the input datum used in the modelling of the pseudo-wells in this work. The parameters shown varied from well to well according to the seismic-stratigraphic interpretation and constraints from nearby DSDP and exploration wells. PWD = Palaeowater depth, SWIT = Sediment Water Interface Temperature HF= Heatflow.

Supplementary Table 2: Summary of main features of the seismostratigraphic units interpreted in West Iberia

Main Inputs Age (Ma)	Top/well pick	Depth (m)	Thickness (m)	Event type	Event	Lithology
0	Unit 1	3645	664	Deposition	Cainozoic Strata	Marl
66	Unit 2	4309	399	Deposition	Late Cret Deposition	Silica-rich carb. mudstone
90	Unit 3	4708	297	Deposition	Cacem Formation	Limestone (shaly)
100	Unit 4	5005	388	Deposition	Break up Sequence	Shale (black)
120	Unit 5	5393	2037	Deposition	Torres Vedras Fmtn.	Sandstone (typical)
142	Unit 6	7430	2231	Deposition	Synrift	Carb.-rich argill. mudstone
198	Unit 7	9661	2296	Deposition	Salt	Salt
210	Silves	11957	620	Deposition	Silves (minimum)	Shale (organic lean, typical)
230	Basement	12577				

Boundary Conditions Age (Ma)	PWD (m)	Age (Ma)	SWIT (.C)	Age (Ma)	HF [mW/m^2]	Age (continued)	HF [mW/m^2]
0	3645	0	20	25	47.16	100	59.4
66	3000	200	20	30	47.72	105	60.22
90	3700			35	48.32	110	60.73
100	2000			40	48.95	115	60.69
120	2000			45	49.61	120	59.75
142	1000			50	50.31	122.2	56.99
198	150			55	51.05	124.4	54.45
210	100			60	51.83	126.6	52.18
				65	52.66	128.8	50.2
				70	53.53	131	48.5
				75	54.45	133.2	47.07
				80	55.41	135.4	45.85
				85	56.41	137.6	44.79
				90	57.43	139.8	43.82

Seismic Units	Age	Two-way traveltime thickness (s)	Average velocity (Velocity taken from Well Lu-1)	Internal character, geometry, and terminations	Simplified probable lithology (Groupe Galice, 1979)
C2-C4	Late Eocene- Holocene	0.4	2614	Various internal reflections of low and high-amplitude.	Comprises siliciclastics hemipelagites, turbidites, contourites and nannofossil oozes.
K3/C	Turonian- Middle Eocene	0.2	3036	Dominated by transparent low-amplitude reflections.	Fine to coarse-grained turbidites and pelagites
K2	Albian to Cenomanian	0.2	3036	High amplitude surface at its base, distinct basal seismic sequence of low amplitude reflections, progradational clinoforms and upper sequence of high-amplitude continuous parallel reflections, high amplitude surface at its top.	Pelagic oozes, local debris-flow deposits and turbidites
K1b	Aptian	0.2	3036	Internal reflections are transparent and in places chaotic but appear to be flat.	Shallow to deep marine siliclastics – pelagic-rich?
K1a	Tithonian to early Aptian	1.1	3708	Continuous and unconformable high-amplitude negative reflections, several rift related geometries.	Shallow to deep marine siliclastics – pelagic-rich?
J2	Sinemurian to Kimmeridgian	1.1	4373	High-amplitude reflections, most internal reflections are continuous and tilted, growth onto tilted blocks, thick syn-rift packages in sub-basins.	Marine carbonates and shales
J1	?latest Triassic-Hettangian	Avg. 1.5	4542	Chaotic to transparent packages, some high amplitude reflections.	Evaporites (Dagorda formation)
Tr	Late Triassic	N/a	4542	Chaotic, loss of seismic character.	Continental siliciclastics (Silves formation)

9 References

Akhmetiev, M.A. and Beniamovski, V.N. 2009. Paleogenefloral assemblages around epicontinental seas and straits in Northern Central Eurasia: proxies for climatic and paleogeographic evolution.Geologica Acta,7,297–309,https://doi.org/10.1344/105.000000278

Allen, M.B. and Armstrong, H.A. 2008. Arabia–Eurasia collision and the forcing of mid-Cenozoic global cool-ing.Palaeogeography, Palaeoclimatology, Palaeoe-cology,265,52–58,https://doi.org/10.1016/j.palaeo.2008.04.021

Alves, T. M. and Abreu Cunha, T. (2018) ‘A phase of transient subsidence, sediment bypass and deposition of regressive–transgressive cycles during the breakup of Iberia and Newfoundland’, Earth and Planetary Science Letters, 484, pp. 168–183. doi: 10.1016/j.epsl.2017.11.054.

Alves, T. M. et al. (2002) ‘Jurassic tectono-sedimentary evolution of the Northern Lusitanian Basin (offshore Portugal)’, Marine and Petroleum Geology, 19(6), pp. 727–754. doi: 10.1016/S0264-8172(02)00036-3.

Alves, T. M. et al. (2006) ‘Mesozoic-Cenozoic evolution of North Atlantic continental-slope basins: The Peniche basin, western Iberian margin’, AAPG Bulletin, 90(1), pp. 31–60. doi: 10.1306/08110504138.

Alves, T. M. et al. (2009) ‘Diachronous evolution of late jurassic-cretaceous continental rifting in the northeast atlantic (west iberian margin)’, Tectonics, 28(4). doi: 10.1029/2008TC002337.

Alves, T.M. (2002) ‘Salt vs. Fault Tectonics on the Western Iberian Margin, Portugal: Controls on Meso-Cenozoic Depositional , PhD thesis, Manchester University.

Anguita, F. and Hernán, F., 2000. The Canary Islands origin: A unifying model. Journal of Volcanology and Geothermal Research, 103(1-4), pp.1-26. DOI: 10.1016/S0377-0273(00)00195-5.

Arthaud, F. and Matte, P. (1977) ‘Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals’, Geological Society of America Bulletin. GeoScienceWorld, 88(9), p. 1305. doi: 10.1130/0016-7606(1977)88<1305:LPSFIS>2.0.CO;2.

Avedik, F. et al. (1982) ‘A seismic refraction and reflexion study of the continent-ocean transition beneath the north Biscay margin’, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 305(1489), pp. 5–25. doi: 10.1098/rsta.1982.0023.

Back, S., Gent, H. v., Reuning, L., Grötsch, J., Niederau, J., & Kukla, P. A. (2011). 3d seismic geomorphology and sedimentology of the chalk group, southern danish north sea. Journal of the Geological Society, 168(2), 393-406. https://doi.org/10.1144/0016-76492010-047

Bacon, M., Simm, R. and Redshaw, T. (2003) 3-D Seismic Interpretation, Seismic. doi: 10.1017/CBO9780511802416.

Bahr, A., Kaboth-Bahr, S. & Karas, C., 2021. The opening and closure of oceanic seaways during the Cenozoic: pacemaker of global climate change? Geological Society, London, Special Publications, 523, pp.141-171. Available at: https://doi.org/10.1144/SP523-2021-54.

Baker, B. and Morgan, P. (1981). Continental rifting: progress and outlook. Eos, 62(29), 585-586. https://doi.org/10.1029/eo062i029p00585-01

Barnett-Moore, N., Müller, D. R., Williams, S. E., Skogseid, J., & Seton, M. (2018). A reconstruction of the North Atlantic since the earliest Jurassic. Basin Research, 30, 160–185. https://doi.org/10.1111/bre.12214

Bengtson, P. et al. (2007) Ammonite and foraminiferal biogeography and the opening of the Equatorial Atlantic Gateway Turonian-Coniacian ammonite biostratigraphy View project HABITATS View project. Available at: https://www.researchgate.net/publication/285675500 (Accessed: 7 December 2018).

Bennet, G., Copestake, P. and Hooker, N. P. (1985) 'Stratigraphy of the Britoil 72/10-1A well, Western approaches', Proceedings of the Geologists' Association. Elsevier, 96(3), pp. 255–261. doi: 10.1016/S0016-7878(85)80007-9.

Berggren, W. A. (1982) 'Role of ocean gateways in climatic change.', Climate in Earth History. Washington, D.C.: National Academies Press, pp.118-125. doi: 10.17226/11798.

Berggren, W.A. and Hollister, C.D. 1977. Plate tectonics and paleocirculation: commotion in the ocean.Tectono-physics,38,11–48,https://doi.org/10.1016/0040-1951(77)90199-8

Bjerrum, C. J., & Surlyk, F. (2001). Jurassic sedimentary evolution of the Danish Basin: sequence stratigraphy, palaeoclimate and basin development. Geological Survey of Denmark and Greenland Bulletin, 1, 1-94. DOI: 10.34194/geusb.v1.4687

Brikiatis, L. (2016) 'Late Mesozoic North Atlantic land bridges', Earth-Science Reviews. doi: 10.1016/j.earscirev.2016.05.002.

Brown, L. and Fisher, W. L. (1977) AAPG Datapages/Archives: Seismic-Stratigraphic Interpretation of Depositional Systems: Examples from Brazilian Rift and Pull-Apart Basins: Section 2. Application of Seismic Reflection Configuration to Stratigraphic Interpretation. Available at: https://archives.datapages.com/data/specpubs/seismic1/data/a165/a165/0001/0200/0213.htm (Accessed: 25 May 2022).

Brun, J. (1999). Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 357(1753), 695-712. https://doi.org/10.1098/rsta.1999.0349

Buck, W. R. (1991). Modes of continental lithospheric extension. Journal of Geophysical Research: Solid Earth, 96(B12), 20161-20178. https://doi.org/10.1029/91jb01485

Bürgmann, R., Pollard, D.D. and Martel, S.J., 1994. Slip distributions on faults: effects of stress gradients, inelastic deformation, heterogeneous host-rock stiffness, and fault interaction. Journal of Structural Geology, 16(12), pp.1675-1690.

Burnham, A. K. (2018) 'Van Krevelen Diagrams', in. Springer, Cham, pp. 1–5. doi: 10.1007/978-3-319-02330-4_67-1.

Butterworth, P. et al. (1999) 'Jurassic non-marine source rocks and oils of the Porcupine Basin and other North Atlantic margin basins', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 5(1), pp. 471–486. doi: 10.1144/0050471.

Callomon, J. H. (1984) 'A Review Of The Biostratigraphy Of The Post-Lower Bajocian Jurassic Ammonites Of Western And Northern North America'.

Callomon, J. H. (2003) 'The Middle Jurassic of western and northern Europe : its subdivisions , geochronology and correlations Te thy', Geological Survey of Denmark and Greenland Bulletin, 1, pp. 61–73.

Capdevila, R. and Mougenot, D. (1988) 'Pre-Mesozoic Basement of the Western Iberian Continental Margin and Its Place in the Variscan Belt', in Proceedings of the Ocean Drilling Program, 103 Scientific Results. Ocean Drilling Program. doi: 10.2973/odp.proc.sr.103.116.1988.

Cedeño, A. et al. (2021) 'Upper Jurassic to Lower Cretaceous source rocks in the Norwegian Barents Sea, part II: Insights from open- and closed-system pyrolysis experiments', Marine and Petroleum Geology, 134, p. 105343. doi: 10.1016/j.marpetgeo.2021.105343.

Chéry, J. et al. (1992) 'Large uplift of rift flanks: A genetic link with lithospheric rigidity?', Earth and Planetary Science Letters. Elsevier, 112(1–4), pp. 195–211. doi: 10.1016/0012-821X(92)90016-O.

Chian, D. et al. (1995) 'Evolution of nonvolcanic rifted margins: New results from the conjugate margins of the Labrador Sea', Geology. GeoScienceWorld, 23(7), p. 589. doi: 10.1130/0091-7613(1995)023<0589:EONRMN>2.3.CO;2.

Chorowicz, J. (2005). The east african rift system. Journal of African Earth Sciences, 43(1-3), 379-410. https://doi.org/10.1016/j.jafrearsci.2005.07.019Wernicke, B. Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen. Nature 291, 645–648 (1981). https://doi.org/10.1038/291645a0

Christopher, J. P. (2003) 'Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum?' Available at: https://pubs.geoscienceworld.org/gsa/geology/article-abstract/31/2/115/192533 (Accessed: 25 May 2022).

Cornford, C. (2005) ‘Petroleum Geology | The Petroleum System’, Encyclopedia of Geology. Elsevier, pp. 268–294. doi: 10.1016/B0-12-369396-9/00247-1.

Cornford, C. (2009) ‘Source Rocks and Hydrocarbons of the North Sea’, Petroleum Geology of the North Sea: Basic Concepts and Recent Advances: Fourth Edition. John Wiley & Sons, Ltd, pp. 376–462. doi: 10.1002/9781444313413.CH11.

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., & Sokoutis, D. (2003). Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. Earth-Science Reviews, 63(3-4), 169-247. https://doi.org/10.1016/s0012-8252(03)00035-7

Coward, M. P. (1990) ‘The Precambrian, Caledonian and Variscan framework to NW Europe’, Geological Society, London, Special Publications. Geological Society of London, 55(1), pp. 1–34. doi: 10.1144/GSL.SP.1990.055.01.01.

Coward, M. P. et al. (2003) The millennium atlas: petroleum geology of the central and northern North Sea. The Geological Society of London.

Cross, T.A. 1986.Tectonic Controls of Foreland Basin Subsidence and Laramide Style Deformation, Western United States. Special Publications International Association of Sedimentologists,.Straits and seaways: end members of a continuum105

Curnelle, R. et al. (1982) ‘The Mesozoic-Tertiary Evolution of the Aquitaine Basin [and Discussion]’, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences. Royal Society, 305, pp. 63–84. doi: 10.2307/37242.

Dalziel, I. W. D. and Dewey, J. F. (2019) ‘The classic Wilson cycle revisited’, Geological Society, London, Special Publications, 470(1), pp. 19–38. doi: 10.1144/SP470.1.

de Graciansky, P. Ch. and Chenet, P.Y. (1979) ‘Sedimentological study of cores 138 to 56 (upper Hauterivian to middle Cenomanian): an attempt at reconstruction of paleoenvironments’, in Sibuet, J.-C., Ryan, W.B.F., Arthur, M.A. et al. (Eds.), Deep-Sea Drilling Project, Preliminary Reports, Part 2, vol. 47, Ocean Drilling Program, College Station, TX, pp. 403–418.

Dean, S. L., Sawyer, D. S. and Morgan, J. K. (2015) ‘Galicia Bank ocean-continent transition zone: New seismic reflection constraints’, Earth and Planetary Science Letters, 413, pp. 197–207. doi: 10.1016/j.epsl.2014.12.045.

DeCelles, P. G. (2004). Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. American Journal of Science, 304(2), 105-168. DOI: 10.2475/ajs.304.2.105

Demaison, G. J. and Moore, G. T. (1980) ‘Anoxic environments and oil source bed genesis’, Organic Geochemistry, 2(1), pp. 9–31. doi: 10.1016/0146-6380(80)90017-0.

Dera, G. et al. (2011) 'Ammonite paleobiogeography during the Pliensbachian–Toarcian crisis (Early Jurassic) reflecting paleoclimate, eustasy, and extinctions', Global and Planetary Change. Elsevier, 78(3–4), pp. 92–105. doi: 10.1016/J.GLOPLACHA.2011.05.009.

Dera, G., Neige, P., Dommergues, J. L., Fara, E., & Laffont, R. (2015). High-resolution dynamics of Early Jurassic marine extinctions: the case of Pliensbachian-Toarcian ammonites (Cephalopoda). Journal of the Geological Society, 172(2), 236-248. DOI: 10.1144/jgs2014-067

Dewey, J.F. and Burke, K.C. (1973) Tibetan, Variscan, and Precambrian Basement Reactivation: Products of Continental Collision. The Journal of Geology, 81, 683-692. https://doi.org/10.1086/627920

Dickie, K., C. E. Keen, G. L. Williams, and S. A. Dehler (2011), Tectonos-tratigraphic evolution of the Labrador margin, Atlantic Canada,Mar. Pet.Geol.,28, 1663–1675, doi:10.1016/j.marpetgeo.2011.05.009

Didyk, B. M. et al. (1978) 'Organic geochemical indicators of palaeoenvironmental conditions of sedimentation', Nature, 272(5650), pp. 216–222. doi: 10.1038/272216a0.

Dinis, J. L. et al. (2008) 'Stratigraphy and allogenic controls of the western Portugal Cretaceous: an updated synthesis', Cretaceous Research. Academic Press, 29(5–6), pp. 772–780. doi: 10.1016/J.CRETRES.2008.05.027.

Doepke (2013) 'Modelling the thermal history of onshore Ireland, Britain and its offshore basins using low-temperature thermochronology.' Available at: https://www.researchgate.net/publication/316686463 (Accessed: 23 May 2022).

Doré, A. G. (1991) 'The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic', Palaeogeography, Palaeoclimatology, Palaeoecology. Elsevier, 87(1–4), pp. 441–492. doi: 10.1016/0031-0182(91)90144-G.

Doré, A. G. (1991). The North Atlantic Igneous Province: A review. In J. D. Parker (Ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference (pp. 123-132). Geological Society. DOI: 10.1144/0040123

Doré, A. G. (1992) 'Synoptic palaeogeography of the Northeast Atlantic Seaway: late Permian to Cretaceous', Geological Society, London, Special Publications. Geological Society of London, 62(1), pp. 421–446. doi: 10.1144/GSL.SP.1992.062.01.31.

Driscoll, N. W. et al. (1995) 'Extensional tectonics in the Jeanne d'Arc Basin, offshore Newfoundland: implications for the timing of break-up between Grand Banks and Iberia', Geological Society, London, Special Publications, 90(1), pp. 1–28. doi: 10.1144/GSL.SP.1995.090.01.01.

Duarte, L. V. et al. (2014) 'Advances in the Stratigraphy and Geochemistry of the Organic-Rich Lower Jurassic Series of the Lusitanian Basin (Portugal)', in Springer Geology. Springer, Cham, pp. 841–846. doi: 10.1007/978-3-319-04364-7_158.

Ebinger, C. (2005). Continental break-up: The East African perspective. Astronomy & Geophysics, 46(2), 16-21.

Eddy, M. P., Jagoutz, O. and Ibañez-Mejia, M. (2017) ‘Timing of initial seafloor spreading in the Newfoundland-Iberia rift’, Geology. GeoScienceWorld, 45(6), pp. 527–530. doi: 10.1130/G38766.1.

Ferrill, D. A., Smart, K. J., & Morris, A. P. (2019). Fault failure modes, deformation mechanisms, dilation tendency, slip tendency, and conduits v. seals. Geological Society, London, Special Publications, 496(1), 75-98. https://doi.org/10.1144/sp496-2019-7

Fjellanger, E., Olsen, T. and Rubino, J.-L. (1996) ‘Sequence stratigraphy and palaeogeography of the Middle Jurassic Brent and Vestland deltaic systems, Northern North Sea’, Norsk Geologisk Tidsskrift. Available at: https://www.researchgate.net/publication/285675500 (Accessed: 7 December 2018).

Folkestad, A. and Satur, N. (2008) ‘Regressive and transgressive cycles in a rift-basin: Depositional model and sedimentary partitioning of the Middle Jurassic Hugin Formation, Southern Viking Graben, North Sea’, Sedimentary Geology. Elsevier, 207(1–4), pp. 1–21. doi: 10.1016/J.SEDGEO.2008.03.006.

Ford, D., & Golonka, J. (2003). Phanerozoic paleogeography, paleoenvironment and lithofacies maps of the circum-Atlantic margins. Marine and Petroleum Geology, 20(3), 249-285. DOI: 10.1016/S0264-8172(03)00086-4

Fürsich, F. T., Schneider, S., Werner, W., López-Mir, B., & Pierce, C. (2021). Life at the continental–marine interface: palaeoenvironments and biota of the alcobaça formation (late jurassic, central portugal), with a formal definition of the unit appended. Palaeobiodiversity and Palaeoenvironments, 102(2), 265-329. https://doi.org/10.1007/s12549-021-00496-x

G. Boillot, D. M. J. G. E. L. W. (1989) ‘Rifting Processes on the West Galicia Margin, Spain: Chapter 23: European-African Margins’. AAPG Special Volumes, 156, pp. 363–377. Available at: http://archives.datapages.com/data/specpubs/structu1/data/a156/a156/0001/0350/0363.htm (Accessed: 11 June 2019).

Gawthorpe, R. L. and Leeder, M. R. (2000). Tectono-sedimentary evolution of active extensional basins. Basin Research, 12(3-4), 195-218. https://doi.org/10.1046/j.1365-2117.2000.00121.x

Ge, Z., Gawthorpe, R.L., Rotevatn, A. and Thomas, M.B., 2017. Impact of normal faulting and pre-rift salt tectonics on the structural style of salt-influenced rifts: the Late Jurassic Norwegian Central Graben, North Sea. Basin Research, 29, pp.674-698. DOI: 10.1111/bre.12219.

Gerges, M. A. (2002) ‘The Red Sea and Gulf of Aden Action Plan—Facing the challenges of an ocean gateway’, Ocean and Coastal Management. Elsevier, 45(11–12), pp. 885–903. doi: 10.1016/S0964-5691(02)00112-6.

Gernigon L., Franke D., Geoffroy L., Schiffer C., Foulger G.R., Stoker M., 2019. Crustal fragmentation, magmatism, and the diachronous opening of the Norwegian-Greenland Sea, Earth Sci. Rev., doi:10.1016/j.earscirev.2019.04.011.10.1016/j.earscirev.2019.04.011

Gibbs, A.D.1984. Structural evolution of extensional basin margins. J. Geol. Soc. Lond. 141, 609-620

Gluyas, J. and Swarbrick, R. (2013) 'Petroleum Geoscience'.

Gordon A. C., Mohriak W. U., Barbosa V. C. F., Mohriak W. U., Danforth A., Post P. J., Brown D. E., Tari G. C., Nemčok M., Sinha S. T. Crustal architecture of the Almada Basin, NE Brazil: an example of a non-volcanic rift segment of the South Atlantic passive margin Conjugate Divergent Margins 2012 369 Geological Society, London, Special Publications, https://doi.org/10.1144/SP369.1

Gouiza, M., Hall, J. and Welford, J. K. (2017) 'Tectono-stratigraphic evolution and crustal architecture of the Orphan Basin during North Atlantic rifting', International Journal of Earth Sciences. Springer Verlag, 106(3), pp. 917–937. doi: 10.1007/S00531-016-1341-0/FIGURES/18.

Gowers, M. B., Holtar, E. and Swensson, E. (1993) 'The structure of the Norwegian Central Trough (Central Graben area)', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 4(1), pp. 1245–1254. doi: 10.1144/0041245.

Graversen, O. (2005) 'The Jurassic-Cretaceous North Sea Rift dome and associated basin evolution', AAPG Annual Convention, 30040, pp. 1–5.

Groupe Galice (1979) 'The continental margin off Galicia and Portugal: acoustical stratigraphy, dredge stratigraphy and structural evolution'. Available at: https://www.researchgate.net/publication/273444083 (Accessed: 25 May 2022).

Hallam, A. (1981) 'A revised sea-level curve for the early Jurassic', Journal of the Geological Society. Geological Society of London, 138(6), pp. 735–743. doi: 10.1144/GSJGS.138.6.0735.

Halland, E. K. (2011) 'CO_2 storage atlas.' Available at: https://www.osti.gov/etdeweb/biblio/21573401 (Accessed: 25 May 2022).

Halland, E. K. et al. (2014) '4. The Norwegian North Sea', in Norwegian petroleum directorate.

Hancock, P. L. (Paul Lewis) & Coward, M. P & Dewey, J. F. (John F.) & Geological Society of London. 1987, Continental extensional tectonics / edited by M.P. Coward, J.F. Dewey, P.L. Hancock. Published for the Geological Society by Blackwell Scientific Publications Oxford [Oxfordshire]

Hansen, J. A. et al. (2020) 'Reservoir assessment of Middle Jurassic sandstone-dominated formations in the Egersund Basin and Ling Depression, eastern Central North Sea', Marine and Petroleum Geology. Elsevier, 111, pp. 529–543. doi: 10.1016/J.MARPETGEO.2019.08.044.

Hansen, T., Clausen, O. and Andresen, K., 2021. Thick- and thin-skinned basin inversion in the Danish Central Graben, North Sea – the role of deep evaporites and basement kinematics. Solid Earth, 12, pp.1719-1747. DOI: 10.5194/se-12-1719-2021.

Haq, B. U., Hardenbol, J. and Vail, P. R. (1987) 'Chronology of Fluctuating Sea Levels Since the Triassic', Science. American Association for the Advancement of Science, 235(4793), pp. 1156–1167. doi: 10.1126/SCIENCE.235.4793.1156.

Harazim, D. et al. (2013) 'Spatial variability of watermass conditions within the European Epicontinental Seaway during the Early Jurassic (Pliensbachian–Toarcian)', Sedimentology. John Wiley & Sons, Ltd, 60(2), pp. 359–390. doi: 10.1111/J.1365-3091.2012.01344.X.

Harzhauser, M., Kroh, A., Mandic, O., Piller, W.E.,Göhlich, U., Reuter, M. and Berning, B. 2007. Bio-geographic responses to geodynamics: a key studyall around the Oligo–Miocene Tethyan Seaway.Zoologischer Anzeiger: A Journal of ComparativeZoology,246, 241–256,https://doi.org/10.1016/j.jcz.2007.05.001

Hesjedal, A. and Hamar, G. P. (1983) 'Lower Cretaceous Stratigraphy and Tectonics of the South-Southeastern Norwegian Offshore', in Petroleum Geology of the Southeastern North Sea and the Adjacent Onshore Areas. Dordrecht: Springer Netherlands, pp. 135–144. doi: 10.1007/978-94-009-5532-5_13.

Hesselbo, S. P. et al. (2007) 'Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal)', Earth and Planetary Science Letters, 253(3–4), pp. 455–470. doi: 10.1016/j.epsl.2006.11.009.

Hiscott, R. N. et al. (1990) 'Comparative Stratigraphy and Subsidence History of Mesozoic Rift Basins of North Atlantic', AAPG Bulletin. GeoScienceWorld, 74(1), pp. 60–76. doi: 10.1306/0C9B2213-1710-11D7-8645000102C1865D.

Hoiland, O., Kristensen, J. and Monsen, T. (1993) 'Mesozoic evolution of the Jæren High area, Norwegian Central North Sea', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 4(1), pp. 1189–1195. doi: 10.1144/0041189.

Holgate, N. E. et al. (2013) 'Sedimentology and sequence stratigraphy of the Middle–Upper Jurassic Krossfjord and Fensfjord formations, Troll Field, northern North Sea', Petroleum Geoscience, 19(3), pp. 237–258. doi: 10.1144/petgeo2012-039.

Hudec, M. R. and Jackson, M. P. A. (2007) 'Terra infirma: Understanding salt tectonics', Earth-Science Reviews, 82(1–2), pp. 1–28. doi: 10.1016/j.earscirev.2007.01.001.

Isaksen, G. H. et al. (1998) 'Controls on the oil and gas potential of humic coals', Organic Geochemistry, 29(1–3), pp. 23–44. doi: 10.1016/S0146-6380(98)00042-4.

Jackson, C. A. L., Kane, K. E. and Larsen, E. (2010) 'Structural evolution of minibasins on the Utsira High, northern North Sea; implications for Jurassic sediment dispersal and reservoir distribution', Petroleum Geoscience. European Association of Geoscientists & Engineers, 16(2), pp. 105–120. doi: 10.1144/1354-079309-011.

Jackson, M. P. A., Cramez, C. and Fonck, J. M. (2000) ‘Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks’, Marine and Petroleum Geology. Elsevier, 17(4), pp. 477–498. doi: 10.1016/S0264-8172(00)00006-4.

Jansa, L. F., Bujak, J. P. and Williams, G. L. (1980) ‘Upper Triassic salt deposits of the western North Atlantic’, Canadian Journal of Earth Sciences. NRC Research Press Ottawa, Canada, 17(5), pp. 547–559. doi: 10.1139/e80-054.

Johannessen, E. R. et al. (1995) ‘Northern limit of the “Brent delta” at the Tampen Spur —a sequence stratigraphic approach for sandstone prediction’, in, pp. 213–256. doi: 10.1016/S0928-8937(06)80070-6.

John M Hunt (1996) ‘Petroleum Geochemistry and Geology.’ John Meacham Hunt.

Jones, D. W. and Underhill, J. R. (2011) ‘Structural and stratigraphic evolution of the Connemara discovery, Northern Porcupine Basin: significance for basin development and petroleum prospectivity along the Irish Atlantic Margin’. doi: 10.1144/1354-079310-035.

Justwan, H. et al. (2005) ‘Late To Middle Jurassic Source Facies And Quality Variations, South Viking Graben, North Sea’, Journal of Petroleum Geology. John Wiley & Sons, Ltd, 28(3), pp. 241–268. doi: 10.1111/J.1747-5457.2005.TB00082.X.

Justwan, H. et al. (2006) ‘Geothermal history and petroleum generation in the Norwegian South Viking Graben revealed by pseudo-3D basin modelling’, Marine and Petroleum Geology. Elsevier, 23(8), pp. 791–819. doi: 10.1016/j.marpetgeo.2006.07.001.

Justwan, H., Dahl, B. and Isaksen, G. H. (2006) ‘Geochemical characterisation and genetic origin of oils and condensates in the South Viking Graben, Norway’, Marine and Petroleum Geology. Elsevier, 23(2), pp. 213–239. doi: 10.1016/J.MARPETGEO.2005.07.003.

Kalani, M., Faleide, J.I. and Gabrielsen, R.H., 2020. Paleozoic-Mesozoic tectono-sedimentary evolution and magmatism of the Egersund Basin area, Norwegian central North Sea. Marine and Petroleum Geology, 122, p.104642.

Kearey, P., Brooks, M. and Hill, I. (2013) ‘An Introduction to Geophysical Exploration’. Available at: https://books.google.com/books/about/An_Introduction_to_Geophysical_Explorati.html?id=hcWKltTxdC8C (Accessed: 25 May 2022).

Keen, C.E. (1987) 'Some important consequences of lithospheric extension', in Geological Society, London, Special Publications, 28, pp. 67-73. Available at: https://doi.org/10.1144/GSL.SP.1987.028.01.07

Kieft, R. L. et al. (2010) ‘Sedimentology and sequence stratigraphy of the Hugin Formation, Quadrant 15, Norwegian sector, South Viking Graben’, Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 7(1), pp. 157–176. doi: 10.1144/0070157.

Klitgord, K. D. and Schouten, H. (1986) ‘Plate kinematics of the central Atlantic’, The Western North Atlantic Region. Geology of North America, pp. 351–378. doi: 10.1130/DNAG-GNA-M.351.

Knott, S. D. et al. (1993) ‘Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins’, Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. doi: 10.1144/0040953.

Korte, C. et al. (2015) ‘Jurassic climate mode governed by ocean gateway’, Nature Communications, 6(1), p. 10015. doi: 10.1038/ncomms10015.

Kyrkjebø, R., Gabrielsen, R. H. and Faleide, J. I. (2004) ‘Unconformities related to the Jurassic–Cretaceous synrift–post-rift transition of the northern North Sea’, Journal of the Geological Society. GeoScienceWorld, 161(1), pp. 1–17. doi: 10.1144/0016-764903-051.

Lamotte, D. F. d., Fourdan, B., Leleu, S., Leparmentier, F., & Clarens, P. d. (2015). Style of rifting and the stages of pangea breakup. Tectonics, 34(5), 1009-1029. https://doi.org/10.1002/2014tc00376

Larsen, L. M., Heaman, L. M., Creaser, R. A., Duncan, R. A., Frei, R., & Hutchison, M. T. (2009). Tectonomagmatic events during stretching and basin formation in the labrador sea and the davis strait: evidence from age and composition of mesozoic to palaeogene dyke swarms in west greenland. Journal of the Geological Society, 166(6), 999-1012. https://doi.org/10.1144/0016-76492009-0384

Lear, C. H., Rosenthal, Y. and Wright, J. D. (2003) ‘The closing of a seaway: Ocean water masses and global climate change’, Earth and Planetary Science Letters. doi: 10.1016/S0012-821X(03)00164-X.

Lervik, K. S. (2006) ‘Triassic lithostratigraphy of the Northern North Sea Basin’, Norsk Geologisk Tidsskrift, 86, pp. 93–115.

Leva López, J. and Steel, R.J. 2015. Laramide signals and architecture of a widespread fluvial sand sheet: Canyon Creek Member, Southern Wyoming, USA.Journal of Sedimentary Research,85, 1102–1122,https://doi.org/10.2110/jsr.2015.67

Liu, S. and Nummedal, D. (2004). Late cretaceous subsidence in wyoming: quantifying the dynamic component. Geology, 32(5), 397. https://doi.org/10.1130/g20318.1

Liu, S., Nummedal, D., & Gurnis, M. (2014). Dynamic versus flexural controls of late cretaceous western interior basin, usa. Earth and Planetary Science Letters, 389, 221-229. https://doi.org/10.1016/j.epsl.2014.01.006

Lundin, E. (2002) ‘North Atlantic – Arctic: Overview of sea-floor spreading and rifting history’.

Mancktelow, N.S., 1999. Finite-element modelling of single-layer folding in elasto-viscous materials: the effect of initial perturbation geometry. Journal of Structural Geology, 21(2), pp.161-177.

Mann, P., Gahagan, L. and Gordon, M. (2003) 'Tectonic Setting of the World's Giant Oil and Gas Fields', AAPG Datapages/Archives.

Mannie, A. S., Jackson, C. A. L. and Hampson, G. J. (2014) 'Structural controls on the stratigraphic architecture of net-transgressive shallow-marine strata in a salt-influenced rift basin: Middle-to-upper jurassic Egersund basin, Norwegian North sea', Basin Research. Blackwell Publishing Ltd, 26(5), pp. 675–700. doi: 10.1111/BRE.12058/.

Marincovich, L. and Gladenkov, A. Yu. (1999) 'Evidence for an early opening of the Bering Strait.' Nature, 397, pp. 149–151.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth and Planetary science letters, 40, 25 – 32, https://doi.org/10.1016/0012-821X(78)90071-7

McLeod, A. E. and Underhill, J. R. (1999) 'Processes and products of footwall degradation, northern Brent Field, Northern North Sea', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 5(1), pp. 91–106. doi: 10.1144/0050091.

Mello, M. R. et al. (1988) 'Organic geochemical characterisation of depositional palaeoenvironments of source rocks and oils in Brazilian marginal basins', in Organic Geochemistry In Petroleum Exploration. Elsevier, pp. 31–45. doi: 10.1016/b978-0-08-037236-5.50009-9.

Merino, I. et al. (2021) 'The Rift and Continent-Ocean Transition Structure Under the Tagus Abyssal Plain West of the Iberia', Journal of Geophysical Research: Solid Earth. John Wiley & Sons, Ltd, 126(11), p. e2021JB022629. doi: 10.1029/2021JB022629.

Merle, O., 2011. A simple continental rift classification. Tectonophysics, 513(1-4), pp.88-95. Available at: https://doi.org/10.1016/j.tecto.2011.10.004.

Minor, K., Steel, R.J., Olariu, C. and Crabaugh, J.P. (2022) 'Facies partitioning of fluvial, wave, and tidal influences across the shoreline-to-shelf architecture in the Western Interior Campanian Seaway, USA', Geological Society, London, Special Publications, 523. Available at: https://doi.org/10.1144/SP523-2022-11.

Minor, K., Steel, R.J., Olariu, C. and Crabaugh, J.P. 2022.Facies partitioning offluvial, wave, and tidal influencesacross the shoreline-to-shelf architecture in the WesternInterior Campanian Seaway, USA.Geological Society,London, Special Publications,523,https://doi.org/10.1144/SP523-2022-11

Mouterde, R. (1979) 'Faciès, biostratigraphie et paléogéographie du Jurassic portugais.' Ciências da Terra / Earth Sciences Journal. Available at: https://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/64 (Accessed: 25 May 2022).

Murillas, J. et al. (1990) ‘Structure and evolution of the Galicia Interior Basin (Atlantic western Iberian continental margin)’, Tectonophysics, 184(3–4). doi: 10.1016/0040-1951(90)90445-E.

Mutterlose, J. et al. (2003) ‘The Greenland-Norwegian Seaway: A key area for understanding Late Jurassic to Early Cretaceous paleoenvironments’, Paleoceanography. American Geophysical Union, 18(1). doi: 10.1029/2001PA000625.

Naylor, D. and Shannon, P. M. (2005) ‘The structural framework of the Irish Atlantic Margin’, Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 6(1), pp. 1009–1021. doi: 10.1144/0061009.

Nichols, G.J. and Fisher, J.A., 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary geology, 195(1-2), pp.75-90.

Nirrengarten, M. et al. (2017) ‘Nature and origin of the J-magnetic anomaly offshore Iberia-Newfoundland: implications for plate reconstructions’, Terra Nova. Wiley/Blackwell (10.1111), 29(1), pp. 20–28. doi: 10.1111/ter.12240.

Oakey, G. N., and Chalmers, J. A. (2012), A new model for the Paleogene motion of Greenland relative to North America: Plate reconstructions of the Davis Strait and Nares Strait regions between Canada and Greenland, J. Geophys. Res., 117, B10401, doi:10.1029/2011JB008942.

Okay, A.I., Zattin, M. and Cavazza, W. 2010. Apatitefission-track data for the Miocene Arabia-Eurasia colli-sion.Geology,38,35–38,https://doi.org/10.1130/G30234.1

Olivet, J. (1996) ‘Kinematics of the Iberian Plate’, Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine. ELF EXPLORATION PRODUCTS, PAU CEDEX, France, 20(1), pp. 131–195. Available at: https://www.cheric.org/research/tech/periodicals/view.php?seq=32207 (Accessed: 27 July 2018).

P. Chenin (2016) ‘Unravelling the impact of inheritance on the Wilson cycle: a combined mapping and numerical modelling approach applied to the North Atlantic rift system.’ Available at: https://www.theses.fr/2016STRAH001 (Accessed: 23 May 2022).

P. Kearey (2002) ‘An Introduction to Geophysical Exploration.’ Philip Kearey, Michael Brooks, Ian Hill - Google Books.

Palcu, D.V. and Krijgsman, W. 2022. The dire straits of Paratethys: gateways to the anoxic giant of Eurasia.Geological Society, London, Special Publications,523,https://doi.org/10.1144/SP523-2021-73Moeller, C., & Faleide, J. I. (2013). The evolution of rift basins: Insights from the Barents Sea. Marine and Petroleum Geology, 43, 1-19. DOI: 10.1016/j.marpetgeo.2013.02.011

Patruno, S., Kombrink, H. and Archer, S. G. (2022) ‘Cross-border stratigraphy of the Northern, Central and Southern North Sea: a comparative tectono-stratigraphic megasequence synthesis’, Geological Society, London, Special Publications, 494(1), pp. 13–83. doi: 10.1144/SP494-2020-228.

Pavelić, D. (2001). Tectonostratigraphic model for the north croatian and north bosnian sector of the miocene pannonian basin system. Basin Research, 13(3), 359-376. https://doi.org/10.1046/j.0950-091x.2001.00155.x

Peace, A.L., Welford, J.K., Ball, P.J. and Nirrengarten, M., 2019. Deformable plate tectonic models of the southern North Atlantic. Journal of Geodynamics, 128, pp.11-37.

Peace, A.L., Welford, J.K., Geng, M., Sandeman, H., Gaetz, B.D. and Ryan, S.S., 2018. Rift-related magmatism on magma-poor margins: Structural and potential-field analyses of the Mesozoic Notre Dame Bay intrusions, Newfoundland, Canada and their link to North Atlantic Opening. Tectonophysics, 745, pp.24-45.

Peacock, D. and Sanderson, D. J. (1994). Geometry and development of relay ramps in normal fault systems. AAPG Bulletin, 78. https://doi.org/10.1306/bdff9046-1718-11d7-8645000102c1865d

Peng, Y., Hagstrom, C.A.et al. 2022. Low-accommodationforeland basin response to long-term transgression: arecord of change from continental-fluvial and marginal-marine to open-marine sequences over 60 000 km2inthe western Canada foreland basin.Marine and Petro-leum Geology,139, 105583,https://doi.org/10.1016/j.marpetgeo.2022.105583

Pepper, A.S. and Corvi, P.J. (1995) Simple Kinetic Models of Petroleum Formation—Part I, Oil and Gas Generation from Kerogen. Marine and Petroleum Geology, 12, 291-319.https://doi.org/10.1016/0264-8172(95)98381-E

Pereira, R. (2013) 'Continental rifting and postbreakup evolution of Southwest Iberia: Tectono-stratigraphic record of the first segment of the North Atlantic Ocean.' Available at: https://orca.cardiff.ac.uk/id/eprint/49558/ (Accessed: 25 May 2022).

Pereira, R. and Alves, T. M. (2012) 'Tectono-stratigraphic signature of multiphased rifting on divergent margins (deep-offshore southwest Iberia, North Atlantic)', Tectonics. doi: 10.1029/2011TC003001.

Pérez-Gussinyé, M. and Reston, T. J. (2001). Rheological evolution during extension at nonvolcanic rifted margins: onset of serpentinization and development of detachments leading to continental breakup. Journal of Geophysical Research: Solid Earth, 106(B3), 3961-3975. https://doi.org/10.1029/2000jb900325

Péron-Pinvidic, G. and Manatschal, G. (2008) 'The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: a new point of view', International Journal of Earth Sciences 2008 98:7. Springer, 98(7), pp. 1581–1597. doi: 10.1007/S00531-008-0337-9.

Péron-Pinvidic, G., Manatschal, G., Minshull, T.A. and Sawyer, D.S., 2007. Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history. Tectonics, [online] Available at: https://doi.org/10.1029/2006TC001970

Peters, K. E. (Kenneth E.), Walters, C. C. (Clifford C.) and Moldowan, J. M. (J. Michael) (2005) 'The biomarker guide.' Cambridge University Press, p. 1155.

Pinheiro, L. et al. (1996) 'The Western Iberia Margin: A Geophysical and Geological overview', Scientific Results. Available at: http://www-odp.tamu.edu/publications/149_SR/VOLUME/CHAPTERS/SR149_01.PDF (Accessed: 27 July 2018).

Porter, S.J., Selby, D., Suzuki, K. and Gröcke, D. 2013.Opening of a trans-Pangaean marine corridor duringthe Early Jurassic: insights from osmium isotopesacross the Sinemurian–Pliensbachian GSSP, RobinHood's Bay, UK.Palaeogeography, Palaeoclimatol-ogy, Palaeoecology,375,50–58,https://doi.org/10.1016/j.palaeo.2013.02.01

Price, J., Dyer, R., Goodall, I., McKie, T., Watson, P., & Williams, G. (1993). Effective stratigraphical subdivision of the humber group and the late jurassic evolution of the uk central graben. Geological Society London Petroleum Geology Conference Series, 4(1), 443-458. https://doi.org/10.1144/0040443

Prosser, S. (1993) 'Rift-related linked depositional systems and their seismic expression', Geological Society, London, Special Publications. Geological Society of London, 71(1), pp. 35–66. doi: 10.1144/GSL.SP.1993.071.01.03.

Prosser, S. (1993). Rift-related linked depositional systems and their seismic expression. Geological Society, London, Special Publications, 71(1), 35-66. https://doi.org/10.1144/gsl.sp.1993.071.01.03

Rasmussen, P.E., Goulding, K.W., Brown, J.R., Grace, P.R., Janzen, H.H. and Korschens, M., 1998. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science, 282(5390), pp.893-896.

Rattey, R. P. and Hayward, A. B. (1993) 'Sequence stratigraphy of a failed rift system: the Middle Jurassic to Early Cretaceous basin evolution of the Central and Northern North Sea', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 4(1), pp. 215–249. doi: 10.1144/0040215.

Ravnås, R. et al. (2000) 'Syn-rift sedimentary architectures in the Northern North Sea', Geological Society, London, Special Publications, 167(1), pp. 133–177. doi: 10.1144/GSL.SP.2000.167.01.07.

Rawson, P. F. and Riley, L. A. (1982) 'Latest Jurassic - Early Cretaceous Events and the "Late Cimmerian Unconformity" in North Sea Area', AAPG Bulletin. GeoScienceWorld, 66(12), pp. 2628–2648. doi: 10.1306/03B5AC87-16D1-11D7-8645000102C1865D.

Redfern, J. et al. (2010) 'An integrated study of Permo-Triassic basins along the North Atlantic passive margin: implication for future exploration', Geological Society, London, Petroleum Geology Conference series. Geological Society of London, 7(1), pp. 921–936. doi: 10.1144/0070921.

Réhault, J.-P. and Mauffret, A. (1979) 'Relationship between tectonics and sedimentation around the Northwestern Iberian Margin.' In: Sibuet, J.-C., Ryan, W.B.F., Arthur, M.A., et al. (Eds.), Deep-Sea Drilling Project, Initial Reports, vol. 47, Ocean Drilling Program, College Station, TX, pp. 663-681.

Roberts, D. G. et al. (1999) 'Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Biscay – a new context for hydrocarbon prospectivity in the deep water frontier', in Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society of London, pp. 7–40. doi: 10.1144/0050007.

Rossi, V. M., Longhitano, S. G., Olariu, C. and Chiocci, F. L. (eds) (2023) 'Straits and Seaways: Controls, Processes and Implications in Modern and Ancient Systems', Geological Society, London, Special Publications, 523, pp. 1–15. First published online January 20, 2023. Available at: https://doi.org/10.1144/SP523-2022-271.

Rossi, V. M., Longhitano, S. G., Olariu, C., & Chiocci, F. L. (2023). Straits and seaways: end members within the continuous spectrum of the dynamic connection between basins. Geological Society, London, Special Publications, 523(1), 85-109. https://doi.org/10.1144/sp523-2022-159

Rowan, M. G. (2014) 'Passive-margin salt basins: hyperextension, evaporite deposition, and salt tectonics', Basin Research. John Wiley & Sons, Ltd, 26(1), pp. 154–182. doi: 10.1111/bre.12043.

Sêco, S.L.R., Silva, R.L., Watson, N., Duarte, L.V., Pereira, A.J.S.C., and Wach, G. (2019) 'Application of petrophysical methods to estimate total organic carbon in Lower Jurassic source rocks from the offshore Lusitanian Basin (Portugal)'. Journal of Petroleum Science and Engineering, in press.

Şengör, A.M.C. and Natal'in, B.A., 2001. Rifts of the world. In: R.E. Ernst and K.L. Buchan, ed., Mantle Plumes: Their Identification Through Time.

Sha, J. (2002) 'Hispanic Corridor formed as early as Hettangian: On the basis of bivalve fossils', Chinese Science Bulletin. Science in China Press, 47(5), p. 414. doi: 10.1360/02tb9096.

Sheriff, R. E. and Geldart, L. P. (1995) 'Exploration Seismology.' R. E. Sheriff, L. P. Geldart - Google Books.

Sibuet, J.-C. and Ryan, W. B. F. (1979) 'Site 398: Evolution of the west Iberian passive continental margin in the framework of the early evolution of the North Atlantic ocean', Initial Reports of the Deep Sea Drilling Project. U. S. Government, 67(2), pp. 673–687. Available at: http://archimer.ifremer.fr/doc/00000/5269/ (Accessed: 27 July 2018).

Siedler, G. et al. (2004) 'Deep-Water Flow in the Mariana and Caroline Basins', Journal of Physical Oceanography. American Meteorological Society, 34(3), pp. 566–581. doi: 10.1175/2511.1.

Sijp, W. P. et al. (2014) 'The role of ocean gateways on cooling climate on long time scales', Global and Planetary Change. Elsevier, 119, pp. 1–22. doi: 10.1016/J.GLOPLACHA.2014.04.004.

Sinclair, I. K. (1995) 'Transpressional inversion due to episodic rotation of extensional stresses in Jeanne d'Arc Basin, offshore Newfoundland', Geological Society, London, Special Publications. Geological Society of London, 88(1), pp. 249–271. doi: 10.1144/GSL.SP.1995.088.01.15.

Skjerven, J., Rijs, F. and Kalheim, J. E. (1983) 'Late Palaeozoic to Early Cenozoic Structural Development of the South-Southeastern Norwegian North Sea', in Petroleum Geology of the Southeastern North Sea and the Adjacent Onshore Areas. Dordrecht: Springer Netherlands, pp. 35–45. doi: 10.1007/978-94-009-5532-5_3.

Smith, A. G. and Pickering, K. T. (2003) 'Oceanic gateways as a critical factor to initiate icehouse Earth', Journal of the Geological Society. doi: 10.1144/0016-764902-115.

Soares, D. M., Alves, T. M. and Terrinha, P. (2012) 'The breakup sequence and associated lithospheric breakup surface: Their significance in the context of rifted continental margins (West Iberia and Newfoundland margins, North Atlantic)', Earth and Planetary Science Letters, 355–356, pp. 311–326. doi: 10.1016/j.epsl.2012.08.036.

Soto, R. et al. (2012) 'Switch of Mesozoic extensional tectonic style in the Lusitanian basin (Portugal): Insights from magnetic fabrics', Tectonophysics. Elsevier, 536–537, pp. 122–135. doi: 10.1016/J.TECTO.2012.03.010.

Srivastava, S. P. et al. (1990) 'Motion of Iberia since the Late Jurassic: Results from detailed aeromagnetic measurements in the Newfoundland Basin', Tectonophysics, 184(3–4), pp. 229–260. doi: 10.1016/0040-1951(90)90442-B.

Srivastava, S. P. et al. (2000) 'Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins', Earth and Planetary Science Letters. Elsevier, 182(1), pp. 61–76. doi: 10.1016/S0012-821X(00)00231-4.

Srivastava, S. P., Verhoef, J. and Macnab, R. (1988) 'Results from a detailed aeromagnetic survey across the northeast Newfoundland margin, Part I: Spreading anomalies and relationship between magnetic anomalies and the ocean-continent boundary', Marine and Petroleum Geology. Elsevier, 5(4), pp. 306–323. doi: 10.1016/0264-8172(88)90025-6.

Stampfli, G. and Borel, G. (2002) 'A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons', Earth and Planetary Science Letters, 196(1–2), pp. 17–33. doi: 10.1016/S0012-821X(01)00588-X.

Stapel, G., Cloetingh, S. and Pronk, B. (1996) 'Quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian basin (western Iberian margin)', Tectonophysics. Elsevier, 266(1–4), pp. 493–507. doi: 10.1016/S0040-1951(96)00203-X.

Steckler, M. S. and Watts, A. B. (1978) ‘Subsidence of the Atlantic-type continental margin off New York’, Earth and Planetary Science Letters. Elsevier, 41(1), pp. 1–13. doi: 10.1016/0012-821X(78)90036-5.

Stoker, M.S., Stewart, M.A. et al. 2016. An overview of the Upper Paleozoic–Mesozoic stratigraphy of the NE Atlantic region. In: Pe´ron-Pinvidic, G., Hopper, J.R., Stoker, M.S., Gaina, C., Doornenbal, J.C., Funck, T. & A´ rting, U.E. (eds) The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution. Geological Society, London, Special Publications, 447. First published online August 11, 2016, updated August 12 2016, https://doi.org/10.1144/SP447.2

Straume, E.O., Gaina, C., Medvedev, S. and Nisancioglu,K.H. 2020. Global Cenozoic Paleobathymetry with afocus on the Northern Hemisphere Oceanic Gateways.Gondwana Research,86, 126–143,https://doi.org/10.1016/j.gr.2020.05.011

Stricker, S., Jones, S. J. and Grant, N. T. (2016) ‘Importance of vertical effective stress for reservoir quality in the Skagerrak Formation, Central Graben, North Sea’, Marine and Petroleum Geology. Elsevier, 78, pp. 895–909. doi: 10.1016/J.MARPETGEO.2016.03.001.

Suan, G. et al. (2015) ‘Calibrating the magnitude of the Toarcian carbon cycle perturbation’, Paleoceanography, 30(5), pp. 495–509. doi: 10.1002/2014PA002758.

Tankard and Welsink (1989) AAPG Datapages/Archives: Mesozoic Extension and Styles of Basin Formation in Atlantic Canada: Chapter 12: North American Margins.

Tate, M. P. and Dobson, M. R. (1989) ‘Late Permian to early Mesozoic rifting and sedimentation offshore NW Ireland.’

Thomas, B. M. et al. (1985) ‘Organic facies and hydrocarbon distributions in the Norwegian North Sea’, Petroleum geochemistry in exploration of the Norwegian Shelf. Proc. NPF conference, Stavanger, 1984. Springer, Dordrecht, pp. 3–26. doi: 10.1007/978-94-009-4199-1_1.

Torsvik, T. H. et al. (2009) ‘A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin’, Geophysical Journal International. Oxford Academic, 177(3), pp. 1315–1333. doi: 10.1111/J.1365-246X.2009.04137.X/2/177-3-1315-FIG013.JPEG.

Trudgill, B. D. and Cartwright, J. A. (1994). Relay-ramp forms and normal-fault linkages, canyonlands national park, utah. Geological Society of America Bulletin, 106(9), 1143-1157. https://doi.org/10.1130/0016-7606(1994)1062.3.co;2

Tucholke, B. E. and Sibuet, J.-C. (2007) ‘Leg 210 Synthesis: Tectonic, Magmatic, And Sedimentary Evolution Of The Newfoundland-Iberia Rift 1’, Proceedings of the Ocean Drilling Program, Scientific Results, 210. doi: 10.2973/odp.proc.sr.210.101.2007.

Turner, H. E. et al. (2017) ‘The age of the Tojeira Formation (Late Jurassic, Early Kimmeridgian), of Montejunto, west-central Portugal’, Swiss Journal of Palaeontology.

Springer International Publishing, 136(2), pp. 287–299. doi: 10.1007/S13358-017-0137-6/TABLES/1.

Umpleby, D. C. (1979),Geology of the Labrador Shelf,Pap. Geol. Surv.Can.,79-13, 34 pp

Underhill, J. R. and Partington, M. A. (1993) ‘Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence’, Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference on Petroleum Geology of NW. Europe, at the Barbican Centre, London, 1, pp. 337–345. doi: 10.1144/0040337.

Uphoff, T. L. (2005) ‘Subsalt (pre-Jurassic) exploration play in the northern Lusitanian basin of Portugal’, AAPG Bulletin. GeoScienceWorld, 89(6), pp. 699–714. doi: 10.1306/02020504090.

van de Schootbrugge, B., Houben, A.J.P.et al. 2020.Enhanced Arctic–Tethys connectivity ended the toar-cian oceanic anoxic event in NW Europe.GeologicalMagazine,157, 1593–1611https://doi.org/10.1017/S0016756819001262

Veekan, P. (2006) ‘Seismic Stratigraphy, Basin Analysis and Reservoir Characterisation.’ Paul P. Veeken - Google Books.

Vítor Duarte, L., José Comas-Rengifo, M. and Louro Silva, R. (2014) ‘Pliensbachian-Toacian Boundary View project Source Rock and Geochemistry of the Central Atlantic Margins View project’. doi: 10.3140/bull.geosci.1476.

Vollset, J. and Dore, A. G. (1984) ‘A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea.’ Available at: https://www.npd.no/globalassets/1-npd/publikasjoner/npd-bulletins/npd-bulletin-3-1984.pdf (Accessed: 25 May 2022).

Wagner, T. and Pletsch, T. (1999) ‘Tectono-sedimentary controls on Cretaceous black shale deposition along the opening Equatorial Atlantic Gateway (ODP Leg 159)’, Geological Society, London, Special Publications. Geological Society of London, 153(1), pp. 241–265. doi: 10.1144/GSL.SP.1999.153.01.15.

Walsh, J.J., Watterson, J., Bailey, W., Childs, C., 1999. Fault relays, bends and branch-lines. Journal of Structural Geology 21, 1019–1026.

Wang, Z., Stout, S. A. and Fingas, M. (2006) ‘Forensic Fingerprinting of Biomarkers for Oil Spill Characterization and Source Identification’, Environmental Forensics, 7(2), pp. 105–146. doi: 10.1080/15275920600667104.

Weissert, H. and Lini, A. (1991) ‘Ice age interludes during the time of Cretaceous greenhouse climate?’, in Müller, D. W., McKenzie, J. A., and Weissert, H. (eds) Controversies in Modern Geology: Evolution of Geological Theories in Sedimentology, Earth History and Tectonics. New York Academic Press, pp. 173–191.

Whiting, L. (2020) ‘From rifting to hyperextension: Upper Jurassic – Lower Cretaceous tectono-stratigraphy of the Porcupine Basin, Irish Atlantic Margin.’ Available at:

https://www.researchgate.net/figure/A-Palaeogeographical-reconstruction-of-the-proto-North-Atlantic-Ocean-during-the_fig1_347504863 (Accessed: 23 May 2022).

Wilson, R. C. L. et al. (1989) 'The Lusitanian Basin of West-Central Portugal: Mesozoic and Tertiary Tectonic, Stratigraphic, and Subsidence History: Chapter 22: European-African Margin', Extensional Tectonics and Stratigraphy of the North Atlantic Margins, 46(4), pp. 341–361. Available at: http://search.datapages.com/data/specpubs/structu1/data/a156/a156/0001/0300/0341.htm.

Wilson, R. C. L., Manatschal, G. and Wise, S. (2001) 'Rifting along non-volcanic passive margins: stratigraphic and seismic evidence from the Mesozoic successions of the Alps and western Iberia', Geological Society, London, Special Publications. Geological Society of London, 187(1), pp. 429–452. doi: 10.1144/GSL.SP.2001.187.01.21.

Withjack, M.O., Schlische, R.W. and Olsen, P.E., 2002. Rift-basin structure and its influence on sedimentary systems.Cowie et al 2005 strain localisation

Wong, K., Ferguson, D., Wieser, P., Morgan, D., Edmonds, M., Tadesse, A. Z., et al. (2023). Focused mid-crustal magma intrusion during continental break-up in Ethiopia. Geophysical Research Letters, 50, e2023GL103257. https://doi.org/10.1029/2023GL103257

Woodgate, R. A. and Aagaard, K. (2005) 'Revising the Bering Strait freshwater flux into the Arctic Ocean', Geophysical Research Letters. John Wiley & Sons, Ltd, 32(2), p. L02602. doi: 10.1029/2004GL021747.

Woodruff, F. and Douglas, R. G. (1981) 'Response of deep-sea benthic foraminifera to Miocene paleoclimatic events, DSDP Site 289', Marine Micropaleontology. Elsevier, 6(5–6), pp. 617–632. doi: 10.1016/0377-8398(81)90024-4.

Ziegler, A. M. (1990) 'Phytogeographic patterns and continental configurations during the Permian Period', Geological Society, London, Memoirs. Geological Society of London, 12(1), pp. 363–379. doi: 10.1144/GSL.MEM.1990.012.01.35.

Ziegler, A. M., Scotese, C. R. and Barrett, S. F. (1982) 'Mesozoic and Cenozoic Paleogeographic Maps', Tidal friction and the Earth's rotation II. Proc. workshop, Bielefeld, 1981. Springer, Berlin, Heidelberg, pp. 240–252. doi: 10.1007/978-3-642-68836-2_17.

Ziegler, P. (1988) 'Evolution of the Arctic-North Atlantic and the Western Tethys: A visual presentation of a series of Paleogeographic-Paleotectonic maps', searchanddiscovery.com, AAPG memoir. Available at: http://www.searchanddiscovery.com/documents/97020/memoir43.htm Evolution of the Arctic-North Atlantic.

Ziegler, P. A. (1975) 'The Geological Evolution of the North Sea Area in the Tectonic Framework of North Western Europe.' Available at: http://www.ngu.no/filearchive/NGUPublikasjoner/NGUnr_316_Bulletin_29_Ziegler_1_27.pdf (Accessed: 27 July 2018).

Ziegler, P. A. (1988). Evolution of Laurasia—A study in Cretaceous paleogeography. In P. A. Ziegler (Ed.), Geological Society of America Memoir (Vol. 171, pp. 1-55). Geological Society of America. DOI: 10.1130/MEM171-p1

Ziegler, P. A. (1992) 'North Sea rift system', Tectonophysics, 208(1–3), pp. 55–75. doi: 10.1016/0040-1951(92)90336-5.