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The Influence of Structural Inheritance and Multiphase Extension on Rift Development, the Northern North Sea

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Abstract The northern North Sea rift evolved through multiple rift phases within a highly heterogeneous crystalline basement. The geometry and evolution of syn-rift depocenters during this multiphase evolution and the mechanisms and extent to which they were influenced by preexisting structural heterogeneities remain elusive, particularly at the regional scale. Using an extensive database of borehole-constrained 2D seismic reflection data, we examine how the physiography of the northern North Sea rift evolved throughout late Permian-Early Triassic (RP1) and Late Jurassic-Early Cretaceous (RP2) rift phases, and assess the influence of basement structures related to the Caledonian orogeny and subsequent Devonian extension. During RP1, the location of major depocenters, the Stord and East Shetland basins, was controlled by favorably oriented Devonian shear zones. RP2 shows a diminished influence from structural heterogeneities, activity localizes along the Viking-Sogn graben system and the East Shetland Basin, with negligible activity in the Stord Basin and Horda Platform. The Utsira High and the Devonian Lomre Shear Zone form the eastern barrier to rift activity during RP2. Toward the end of RP2, rift activity migrated northward as extension related to opening of the proto-North Atlantic becomes the dominant regional stress as rift activity in the northern North Sea decreases. Through documenting the evolving syn-rift depocenters of the northern North Sea rift, we show how structural heterogeneities and prior rift phases influence regional rift physiography and kinematics, controlling the segmentation of depocenters, as well as the locations, styles, and magnitude of fault activity and reactivation during subsequent events.

Key Points:
- The regional evolution of the northern North Sea rift is documented throughout late Permian-early Triassic and Late Jurassic-Early Cretaceous rift phases
- Preexisting structural heterogeneities may control the initial geometry of rift-related faults and associated syn-rift depocenters when favorably oriented, and may also segment faults and depocenters
- Rift activity migrates throughout the evolution of the rift, showing a decreased influence from structural inheritance and increased localization of activity during subsequent phases

Supporting Information:
- Supporting Information S1

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1. Introduction

Continental rifts often develop through multiple phases of extension within lithosphere containing structural heterogeneities inherited from earlier orogenic events. At the regional scale, faults from prior rift phases and preexisting structural heterogeneities may be reactivated in some areas during later rift phases while remaining inactive in others, resulting in the migration of syn-rift depocenters and fault activity throughout the evolution of a rift. The evolution of rift systems throughout these multiple superposed tectonic events records the influence of any preexisting structural heterogeneities within the lithosphere.

Preexisting structures, along with early phases of rifting, can exert a considerable influence over the distribution of fault activity and the geometry and evolution of syn-rift depocenters during rifting. Pervasive basement fabrics can directly control the geometry of faults and the (rift) basins they bound (e.g., Daly et al., 1989; Fazlikhani et al., 2017; Gontijo-Pascutti et al., 2010; Morley et al., 2004; Paton & Underhill, 2004; Phillips et al., 2016; Phillips et al., 2017; Salomon et al., 2015; Skyttä et al., 2019; Vasconcelos et al., 2019). Discrete structures may also locally perturb the regional stress field, causing faults to strike oblique to the regional extension direction (Corti, 2008; Corti et al., 2007; Morley, 2010, 2017; Philippon et al., 2015; Rotevatn et al., 2018; Samsu et al., 2019). In other instances, prerift basement structures may also retard lateral fault propagation and thus cause fault and rift segmentation (Brune et al., 2017; Fossen et al., 2016; Koopmann et al., 2014). Earlier phases of extension may also modify the crustal and lithospheric structure

of rift systems. Faults related to earlier rift phases interact with, and may exhibit controls over the growth of newly formed normal faults (e.g., Bell et al., 2014; Claringbould et al., 2017; Deng, Fossen, et al., 2017; Duffy et al., 2015; Henstra et al., 2015; Henstra et al., 2019; Morley, 2017; Nixon et al., 2014); while, at the whole-rift scale, lithospheric thinning associated with earlier phases of extension may focus strain during later rift phases (e.g., Boone et al., 2018; Brune et al., 2017; Claringbould et al., 2017; Cowie et al., 2005; Naliboff & Buiter, 2015; Odinsen et al., 2000). Previous studies often focused on local (less than tens of kilometers) scale aspects of the influence of preexisting structural heterogeneities on rift geometry and kinematics, with relatively few studies examining the regional, whole-rift (hundreds of kilometers) scale (Corti, 2009; Daly et al., 1989; Fazlikhani et al., 2017; Morley, 2017). Furthermore, these studies often do not consider how structural inheritance is able to influence rift physiography along-strike and in 3-D, and how preexisting structural heterogeneities may influence fault reactivation and therefore control the location and geometry of syn-rift depocenters throughout multiple rift phases.

In this study, we focus on the northern North Sea rift located between the UK and Norway, which represents a failed rift marginal to the site of eventual North Atlantic breakup (e.g., Coward et al., 2003; Dore et al., 1997; Kristoffersen, 1978; Roberts et al., 1999). The underlying crystalline basement of the rift is highly heterogeneous, containing numerous structures formed during the Caledonian orogeny and a subsequent period of Devonian extension (e.g., Andersen & Jamtveit, 1990; Bird et al., 2014; Færseth et al., 1995; Fazlikhani et al., 2017; Fossen et al., 2016; Lenhart et al., 2019; McClay et al., 1986; Phillips et al., 2016; Reeve et al., 2013; Scisciani et al., 2019). The northern North Sea rift formed in response to two main phases of extension, initiating in the late Permian-Early Triassic (RP1) with a further phase in the Late Jurassic-Early Cretaceous (RP2; e.g., Coward et al., 2003; Færseth, 1996; Ziegler, 1992).

Due to its long history of hydrocarbon exploration and production, the northern North Sea rift contains an abundance of geophysical and geological data, including near-complete coverage by 2-D and 3-D seismic reflection data and >6,000 boreholes. This rich subsurface data set has illuminated the tectono-stratigraphic evolution of the North Sea rift (e.g., Evans et al., 2003), although, due to a previous relative scarcity of well and seismic data at deeper structural levels, a number of key questions regarding the early stages of rift evolution remain. Well data are typically collected at relatively shallow (2–3 km), more economic depths, with few wells penetrating deeper areas, particularly in the hanging walls of major faults. Previously, imaging of basement structures was confined to regional seismic sections, often limited to 2-D and at the expense of resolving shallow structure (BIRPS and ECORS, 1986; Fossen et al., 2014; Gabrielsen et al., 2015; Klemperer & Hobbs, 1991). However, more recently basement structures have been resolved beneath the northern North Sea rift, particularly where they are situated at relatively shallow depths on the rift margins (Bird et al., 2014; Fazlikhani et al., 2017; Lenhart et al., 2019; Patruno et al., 2019; Phillips et al., 2016; Reeve et al., 2013).

Using key borehole-constrained stratigraphic horizons and intervening time-thickness maps covering the entire northern North Sea rift (100,000 km^2), along with a detailed catalogue of the various basement structures (Fazlikhani et al., 2017; Fichler et al., 2011; Fossen et al., 2016; Lundmark et al., 2013), we characterize the structural style and depocenter geometry of the rift system throughout late Permian-Early Triassic and Late Jurassic-Early Cretaceous rift phases. The relatively well constrained basement structures beneath the northern North Sea rift (Færseth et al., 1995; Fazlikhani et al., 2017; Lenhart et al., 2019; Lundmark et al., 2013; Phillips et al., 2016; Reeve et al., 2013), in combination with the abundance of geophysical data imaging the deeper levels of the rift, make it the ideal natural laboratory in which to study how preexisting structures and multiple phases of rifting influence the geometric and kinematic development of rift systems.

This represents a detailed, regional scale study of depocenter geometry and evolution throughout the multiphase Permian-Cretaceous evolution of the northern North Sea, a type example of a multiphase rift system influenced by structural inheritance. We relate our regional-scale observations to individual basin-scale studies in the northern North Sea, incorporating these earlier studies into a wider regional context, and other regional studies of rift systems elsewhere. By focusing on the detailed rift physiography and analyzing the evolving depocenter distribution and fault activity across the northern North Sea rift, we are able to document along-strike changes in rift physiography throughout multiple rift phases, and to understand how this physiography was influenced by structural inheritance in 3-D. This study

showcases the detailed regional evolution of a multiphase rift system and highlights the variable influence of preexisting structural heterogeneities spatially across the rift during initial and subsequent phases of rifting.

2. Regional Setting and Evolution of the North Sea

The northern North Sea rift, as referred to in this study, encompasses an ~250 × 450 km area (~100,000 km^2) between the East Shetland Platform and the western Norway coastline, and stretching from the along-strike continuation of the Møre-Trondelag Fault complex in the north to the E-W parallel with the southern tip of Norway (~58°N) in the south (Figure 1).

The crystalline basement beneath the northern North Sea rift is exposed onshore in Norway, the Shetland Islands and in northern Scotland. The basement initially formed during the Proterozoic Sveconorwegian orogeny (Roffeis & Corfu, 2013; Slagstad et al., 2013), before being reworked during the Ordovician-Devonian Caledonian orogeny (Coward, 1990; McKerrow et al., 2000; Milnes et al., 1997; Roberts, 2003; Wiest et al., 2018). The Scandian phase of the Caledonian orogeny involved the collision of Baltica and Laurentia and the closure of the Iapetus Ocean (Gee et al., 2008), with the further collision of Avalonia to the south (McKerrow et al., 2000). Allocthonous nappes, including continental terranes from Baltica and Laurentia and oceanic terranes from the Iapetus Ocean (Fossen & Dunlap, 1998; Hossack & Cooper, 1986; Lundmark et al., 2013), were transported ESE on a décollement composed of mechanically weak Cambrian-Ordovician shales and phyllites, and emplaced onto the western margin of Baltica (Fossen & Rykkelid, 1992; Milnes et al., 1997).

During the Early Devonian, Caledonian thrusting was succeeded by E-W to NW-SE oriented extension, affecting an area stretching from onshore western Norway in the east to NE Scotland (Orcadian Basin) and Greenland in the west (Fossen, 1992, 2010; McClay et al., 1986; Rey et al., 1997; Rotevatn et al., 2018). This extension was initially accommodated by extensional reactivation of the basal Caledonian thrust zone (Mode I extension of Fossen, 1992), which accounted for around 30 km of extension across southern Norway. Subsequent extension was accommodated by the formation of kilometer-scale shear zones that offset the entire Caledonian nappe sequence and which extend deep into the underlying crust (Mode II extension of Fossen, 1992). Devonian shear zones and basins are identified onshore western Norway (Fossen & Rykkelid, 1992; Milnes et al., 1997; Seranne & Seguret, 1987; Vetti & Fossen, 2012). These shear zones extend offshore beneath the northern North Sea rift and, along with additional structures that are not present onshore, are expressed in seismic reflection data as packages of coherent intrabasement reflectivity (e.g., Bird et al., 2014; Fazlikhani et al., 2017; Fossen et al., 2016; Lenhart et al., 2019; Phillips et al., 2016).

Following Devonian extension, the North Sea experienced further phases of extension and compression during the Palaeozoic and Mesozoic (Coward et al., 2003; Ziegler, 1992). E-W oriented extension and associated magmatism occurred across central Europe and the southern North Sea during the late Carboniferous-early Permian, mainly affecting the southern part of the study area (Figure 1; Pegrum, 1984; Phillips et al., 2017; Wilson et al., 2004). Postrift thermal subsidence following late Carboniferous-early Permian extension led to the formation of the North and South Permian basins, and deposition of the evaporite-dominated Zechstein Supergroup, which influenced depocenter distribution in the southern section of the study area (Jackson & Stewart, 2017; Stewart et al., 2007; Stewart & Coward, 1995). The first major rift phase to have affected the northern North Sea rift initiated in the late Permian and continued into the Early Triassic (here termed Rift Phase 1 (RP1); Coward, 1995; Coward et al., 2003; Færseth, 1996; Roberts et al., 1995; Ziegler, 1992). Extension associated with RP1 postdates the deposition of the Upper Permian Zechstein salt in the south of the area (Jackson & Lewis, 2013; Ziegler, 1992). The regional extension direction during RP1 is inferred to be E-W, based on the emplacement of N-S striking Permian-Triassic dykes onshore Norway (Fossen & Dunlap, 1999), forming a dominantly N-S oriented rift (Bell et al., 2014; Coward, 1995; Færseth, 1996; Roberts et al., 1995; Ter Voorde et al., 2000; Ziegler, 1992).

A period of relative tectonic quiescence followed RP1 (Coward et al., 2003; Ziegler, 1992), although some faults remained active during this so-called “interrift” period (Claringbould et al., 2017; Deng, Fossen, et al., 2017). Early-Middle Jurassic thermal doming in the Central North Sea resulted in the erosion

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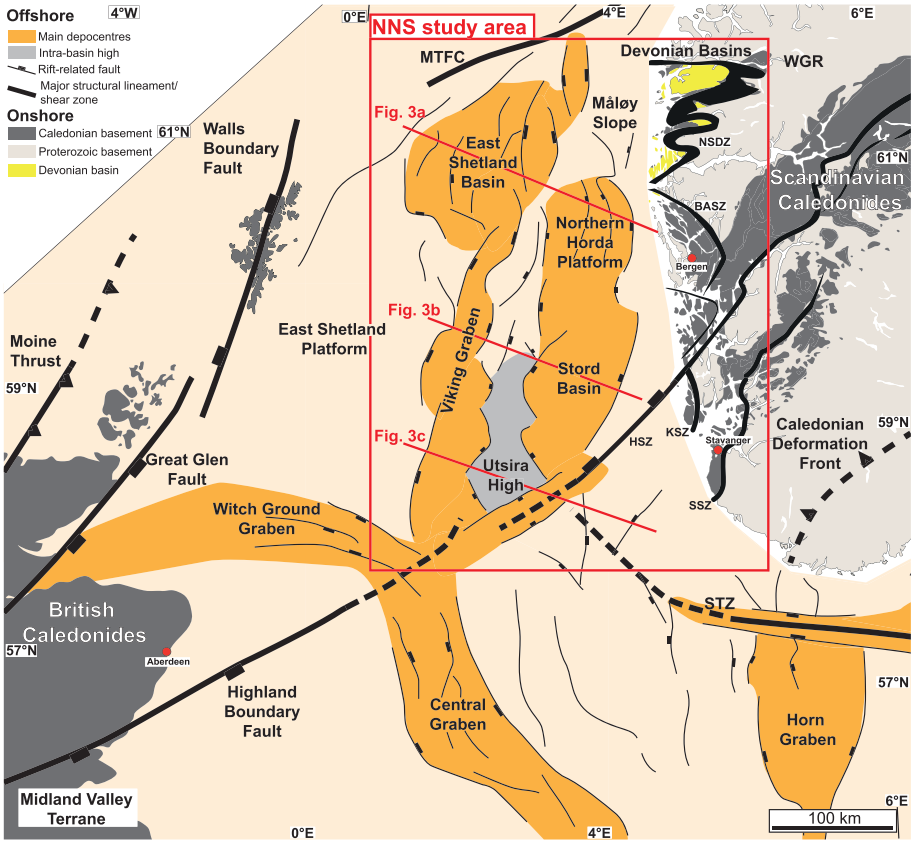

Figure 1. Regional setting of the North Sea between the UK and Norway. The northern North Sea rift (NNS) study area is shown by the red rectangle. The locations of major lineaments identified onshore and offshore are marked by thick black lines after Fazlikhani et al. (2017). Onshore Norway basement geology from Fossen et al. (2016); gray areas correspond to Caledonian nappes, beige colors represent Proterozoic-aged basement while yellow colors indicate Devonian basins. The main offshore rift axes are shown in orange. MTFC = Møre-Trondelag Fault Complex, WGR = Western Gneiss Region, NSDZ = Nordfjord-Sogn Detachment Zone, BASZ = Bergen Arc Shear Zone, HSZ = Hardangerfjord Shear Zone, KSZ = Karmøy Shear Zone, SSZ = Stavanger Shear Zone, STZ = Sorgenfrei-Tornquist Zone.

and removal of large thicknesses of strata across large parts of the North Sea (Davies et al., 1999; Quirie et al., 2019; Underhill & Partington, 1993). The collapse of this thermal dome in the Middle to Late Jurassic was followed by a second rift phase (here termed Rift Phase 2; RP2), with activity lasting until the Early Cretaceous (Coward et al., 2003; Færseth, 1996; Færseth et al., 1997; Underhill & Partington, 1993; Ziegler, 1992). Rift activity localized onto the ENE-WSW striking Witch Ground Graben in the east, the NNW-SSE striking Central Graben in the south, and the N-S striking Viking Graben in the northern North Sea (Coward et al., 2003; Davies et al., 2001; Færseth, 1996; Odinsen et al., 2000; Roberts et al., 1995; Ter Voorde et al., 2000).

The extension direction during RP2 across the northern North Sea is highly debated, with numerous studies stating that the extension direction was E-W similar to RP1 (Bartholomew et al., 1993; Bell et al., 2014; Brun & Tron, 1993; Roberts et al., 1990), whereas others suggest that the extension direction rotated to NW-SE during RP2 (Færseth, 1996; Færseth et al., 1997). During the latter stages and following RP2, the main area of extension migrated northward to the Norwegian Sea and the opening of the proto-North Atlantic Ocean as the Artic and Atlantic rift systems to the north and west linked (Roberts et al., 1999; Stewart et al., 1992; Ziegler, 1992). The offshore extension of the Møre-Trondelag Fault Complex (Figure 1) formed the boundary between the proto-North Atlantic and North Sea rifts (Dore et al., 1997).

3. Data and Methods

3.1. Data

This study uses a compilation of 29 2-D seismic reflection surveys (~315,000 km total length) from the northern North Sea rift (see Fazlikhani et al., 2017). These surveys display a range of orientations, were acquired over a range of time periods (1980–2012), and have different acquisition and processing parameters (see Table S1 in the supporting information). Seismic line spacing is typically ~3 km (~6 km across parts of the East Shetland Basin), allowing the correlation of stratigraphic horizons and basement structures between individual lines. The majority of the sections used in this study are of a high quality and image down to ~9s TWT, allowing us to constrain deeper structures and thus the early rift history. Stratigraphic horizons are tied to a large number of wells, of which 72 penetrate crystalline basement (see Table S2; Fazlikhani et al., 2017). Structural measurements were converted from the time to the depth domains using the velocity model of Fazlikhani et al. (2017), with those at deeper levels of the basin converted using interval velocities from Christiansson et al. (2000). Although parts of these surveys have been interpreted in local studies (e.g., Claringbould et al., 2017; Deng, Fossen, et al., 2017; Duffy et al., 2015), this represents one of the first studies to integrate the available data with observations from these local studies to resolve the regional multiphase rift evolution of the whole of the northern North Sea.

3.2. Seismic Interpretation

We map borehole-constrained stratigraphic horizons to describe the present-day rift geometry at different structural levels. These horizons represent (i) the base of the late Permian-Early Triassic rift sequence (termed “Base RP1”), affected by both RP1 and RP2; (ii) the base of the late Middle Jurassic-Early Cretaceous rift sequence (termed “Base RP2”), showing deformation solely related to RP2 and later activity; (iii) the Base Cretaceous Unconformity (BCU), representing a prominent horizon within the upper RP2 interval (termed “Near Top-RP2”); and (iv) a conservative “Post-rift” horizon corresponding to the top Cretaceous, unaffected by RP1 and RP2 activity.

Due to the large areal extent of these surfaces, and the potentially diachronous nature of rift activity across the rift, the mapped surfaces often correspond to different lithostratigraphic units in different areas and subbasins (Figure 2). The Base RP1 surface typically corresponds to the base of the Triassic (i.e., base Smith Bank or Teist formation; Figure 2), or younger strata where the Triassic is not present (i.e., structural highs or platform areas). One exception is that, where present, the Base RP1 horizon is represented by the base of the Zechstein Supergroup (Figure 2). Although this represents a Pre-RP1 horizon, it forms a regionally prominent reflection and, in contrast to the Top Zechstein horizon (i.e., the base Triassic), does not include any short-wavelength relief associated with salt mobilization that would obscure our observations. The Base RP2 surface corresponds to the base of the Middle Jurassic Hugin and Sandnes formations in the south, and the base Heather formation elsewhere. The BCU is typically taken to mark the syn- to post-RP2 transition across the northern North Sea rift, although some RP2 fault activity postdates this horizon (Bell et al., 2014; Gabrielsen et al., 2001; Kyrkjebø et al., 2004). In the basin, this typically corresponds to the base Åsgard formation (Figure 2), although it often merges with younger unconformities in shallower areas. The mapped Post-rift horizon is defined by the top Shetland Group across the entire northern North Sea rift (Figure 2).

The Base RP1 surface was mapped with moderate to high confidence across the Åsta Graben, Horda Platform, Stord Basin, and East Shetland Basin due to an abundance of well control and its relatively shallow burial depth. Where it is situated at deeper levels beneath the axis of the northern North Sea rift, such as in the Viking and Sogn grabens, we are unable to accurately identify the exact reflection representing the Base RP1 horizon, although we can identify basin-bounding faults that extend through and offset this interval. Due to this “corridor of uncertainty” beneath the North Viking and Sogn grabens, we are often unable to determine the true depth to the Base RP1 horizon, resulting in lower confidence in our interpretation of the depth and thickness of RP1 depocenters in these areas. The shallower horizons were mapped with high confidence across the rift.

We calculated time-thickness maps between our key stratigraphic surfaces to examine the multiphase evolution of the complete northern North Sea rift. The time-thickness map between the Base RP1 and Base RP2 defines syn-rift strata associated with RP1 (Figure 2). This map incorporates the relatively thin Pre-RP1 Zechstein Supergroup in the south as well as some RP1 postrift strata (i.e., Late Triassic-Middle Jurassic) in

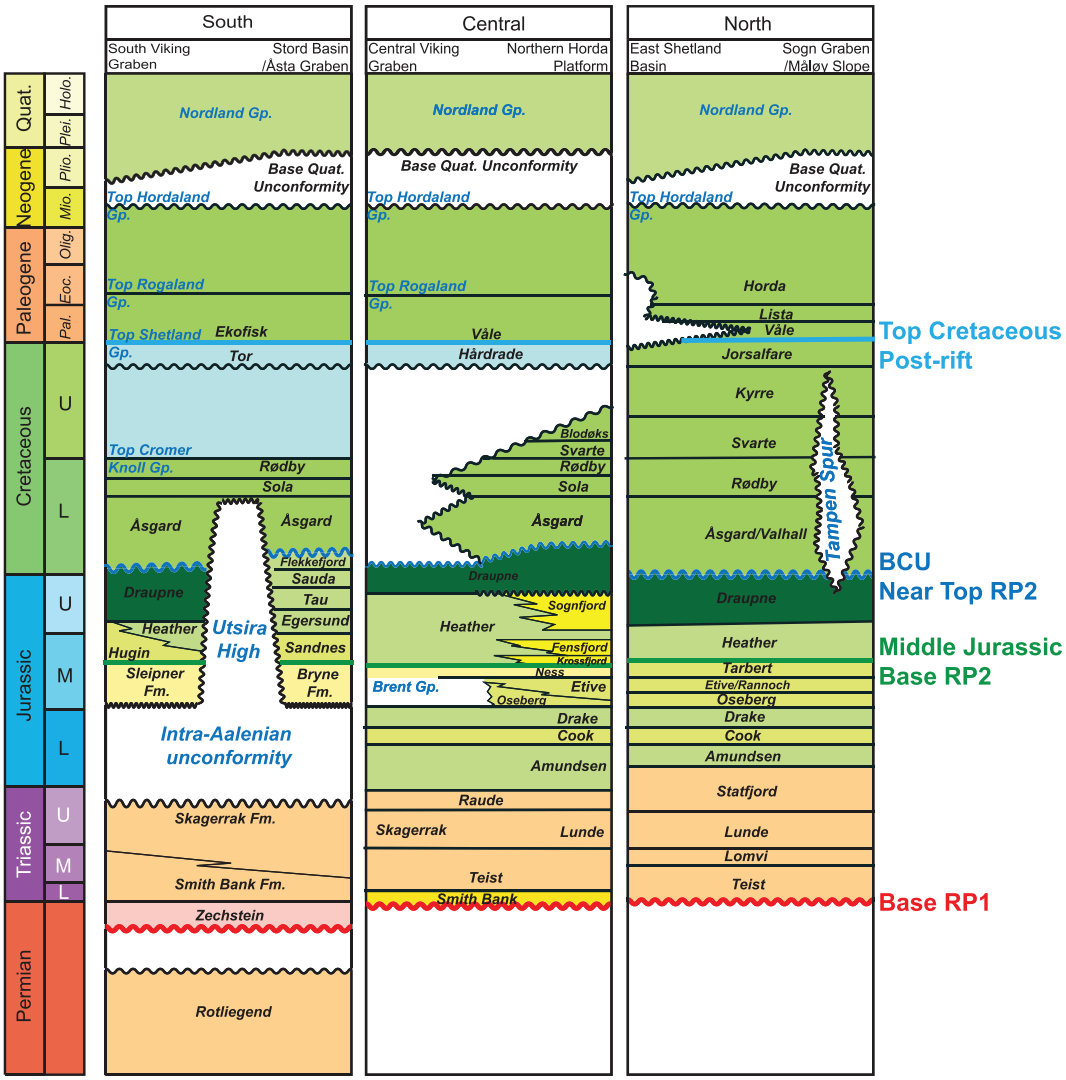

Figure 2. Regional stratigraphic columns across various subbasins of the northern North Sea rift, showing the different lithostratigraphic units that comprise temporally consistent surfaces referred to and mapped throughout this study. Compiled from Patruno and Reid (2016) and NPD (2014).

the upper parts of the interval beneath the Base RP2 surface. Including these relatively thin packages of pre- and post-RP1 strata in the much thicker RP1 time-thickness map does not impact our ability to identify the various syn-rift depocenters, particularly as we also use seismic sections to identify wedge-shaped packages of growth strata that thicken into the hanging walls of faults to confirm fault activity during each rift phase. The Base RP2–Near Top-RP2 time-thickness map includes all Jurassic strata and records the majority of RP2 syn-rift strata. This is referred to as the "RP2" time-thickness map. The Near Top-RP2–Post-rift time-thickness map incorporates any Late RP2 syn-rift strata and a significant postrift interval that records the migration of activity from the North Sea to proto North Atlantic opening, and subsequent onset of postrift thermal subsidence in the northern North Sea. This is referred to as the Late-syn- to Post-RP2 time-thickness map.

4. Preexisting Structural Framework of the Northern North Sea

Based on seismic reflection transects and observations from previous studies, we establish the presence, orientations, and geometry of preexisting structural heterogeneities beneath the northern North Sea rift (Figures 3 and 4), which we later compare to that of syn-rift depocenters during the evolution of the rift.

Crystalline basement is penetrated by numerous wells across the northern North Sea and has been interpreted in terms of the tectonic units identified onshore in Norway and Scotland (Lenhart et al., 2019;

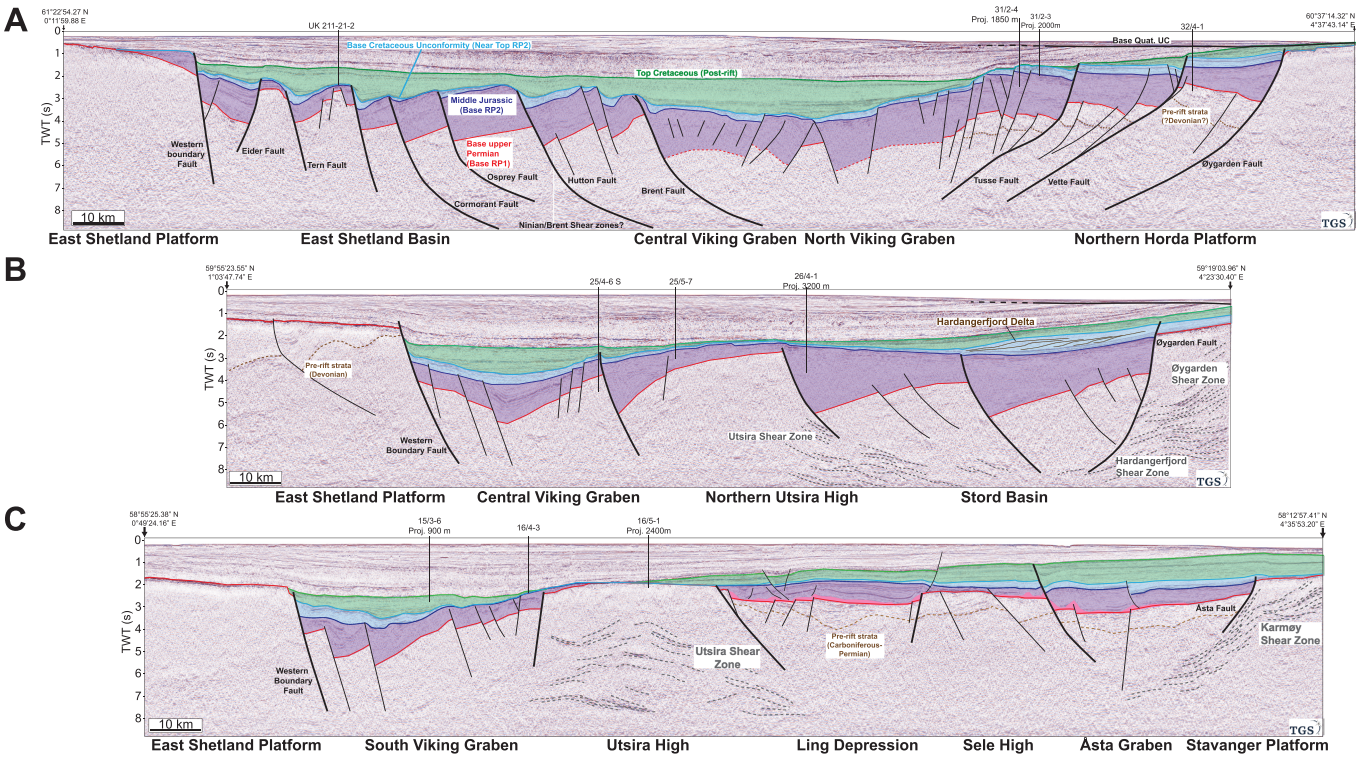

Figure 3. Regional seismic sections across the northern North Sea rift from north to south. See Figure 1 for section locations and see supporting information for uninterpreted sections. (a) Interpreted seismic section stretching from the East Shetland Basin in the west to the Northern Horda Platform in the east. Key surfaces and structures referred to in this study are identified. (b) Interpreted seismic section across the central portion of the rift, from the Central Viking Graben to the Stord Basin. Note the presence of Devonian basins beneath the Base RP1 surface on the East Shetland Platform and the interpretation of the Utsira Shear zone and the Hardangerfjord and Øygarden shear zones beneath the northern Utsira High and Stord Basin, respectively. (c) Interpreted seismic section across the southern portion of the rift, stretching from the South Viking Graben to the Åsta Graben and Stavanger Platform. Prerift strata of Carboniferous-Permian age are identified beneath the Ling Depression, Sele High, and Åsta Graben, with the Utsira and Karmøy shear zones present beneath the Utsira High and Åsta Graben/Stavanger Platform, respectively. Note that the Utsira High forms a series of subhorizontal to east dipping strands in this area. Data courtesy of TGS ((a) NSR06-31182.0009614, (b) NSR06-31154.0015823, (c) NSR05-211321.0015647).

Lundmark et al., 2013; Riber et al., 2015; Slagstad et al., 2011). Well penetrations across the Utsira High, a long-lived structural high in the center of the northern North Sea rift, indicate that, at least in the top few meters penetrated by the wells, crystalline basement is dominantly granitic (e.g., wells 16/1-15, 16/5-1, 16/6-1; Figure 4; Lundmark et al., 2013; Riber et al., 2015; Slagstad et al., 2011). Slagstad et al. (2011) and Lundmark et al. (2013) present U-Pb ages suggesting that the granitic basement of the Utsira High formed part of a volcanic arc terrane incorporated into the Caledonian orogeny. This volcanic arc terrane may also be present beneath the East Shetland Basin and East Shetland Platform, and the Midland Valley Terrane onshore Scotland (Figure 1; Fichler et al., 2011; Lundmark et al., 2013).

Mylonitic shear zones associated with the Caledonian orogeny and late syn- to post-Caledonian Devonian extension have been interpreted on seismic reflection data beneath the northern North Sea rift, where they are characterized by coherent packages of intrabasement reflectivity (Fazlikhani et al., 2017; Fossen & Hurich, 2005; Hurich & Kristoffersen, 1988; Phillips et al., 2016; Reeve et al., 2013). Here we briefly outline the general geometries of those shear zones referred to throughout this study (for a more detailed description of the shear zones, see Fazlikhani et al., 2017). In the northern part of the study area, the east dipping Tampen Shear Zone strikes N-S beneath the eastern margin of the East Shetland Basin. Further west, the N-S to NE-SW striking Ninian and Brent shear zones splay southward away from the Tampen Shear Zone (Figures 3a and 4; Fazlikhani et al., 2017). Along the eastern rift margin, west plunging corrugations associated with the offshore Nordfjord-Sogn Detachment increase in dip toward the Sogn Graben (Lenhart et al., 2019; Figure 4). Some of these corrugations appear spatially and perhaps kinematically linked with the E-W to NE-SW striking Lomre Shear Zone (Figure 4; Fazlikhani et al., 2017). The NE-SW striking Hardangerfjord Shear Zone and the N-S striking Øygarden Shear Zone lie in the footwall of the Øygarden

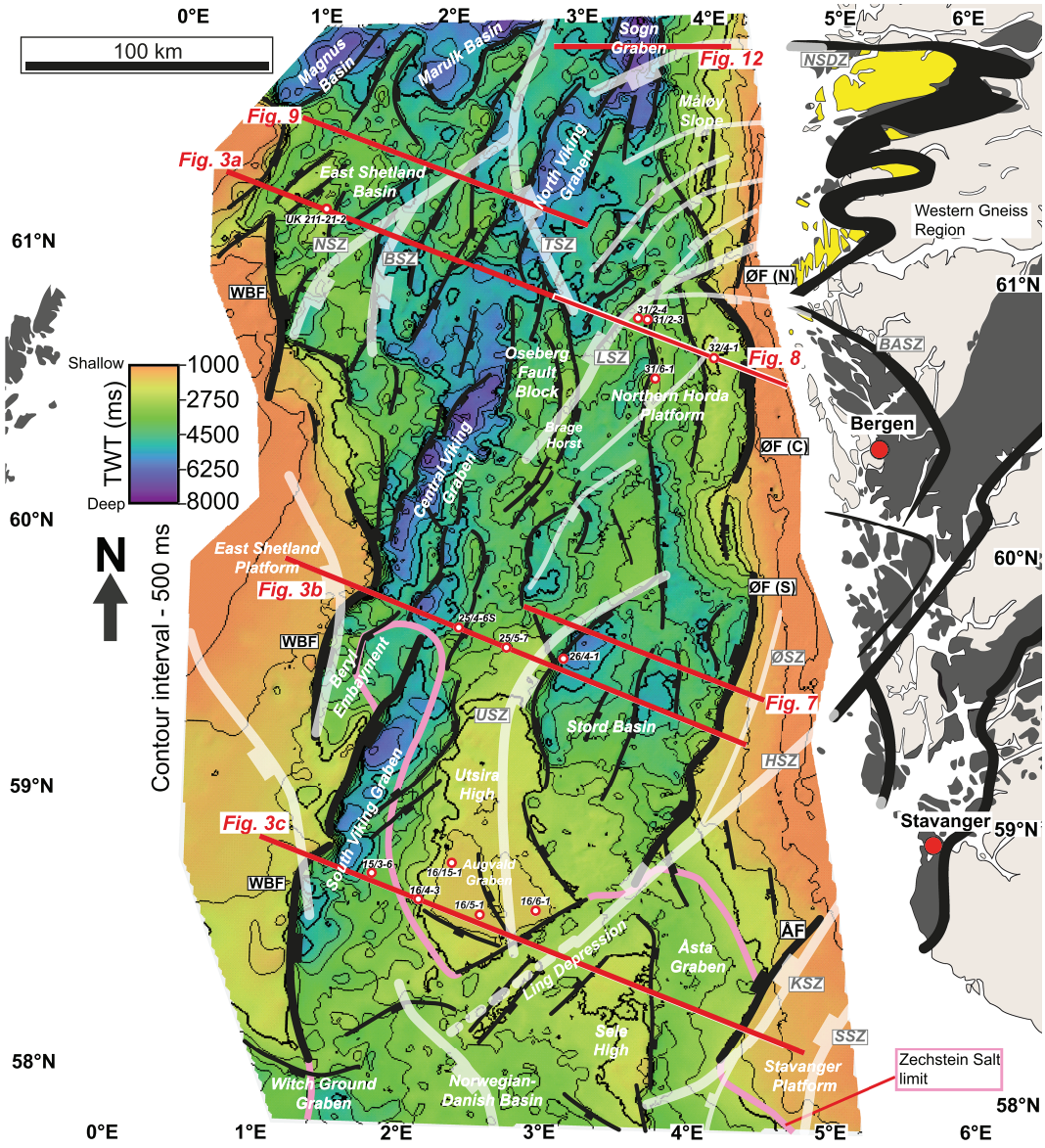

Figure 4. Two-way-time (TWT) structure map of the Base RP1 structure map, modified after Fazlikhani et al. (2017). See Figures 2 and 3 for structural level. The offshore extensions of Devonian shear zones are shown by white translucent lines (after Fazlikhani et al., 2017), with those referred to in the study labeled in gray. The Utsira High forms an intrabasinal high in the south of the area. The pink line represents the northern limit of mobile salt of the Zechstein Supergroup. Major structural lows include the Stord Basin, East Shetland Basin, and the Viking Graben and Sogn Graben. Faults: WBF = Western Boundary Fault, ØF (S/C/N) = Øygarden Fault (South/Central/North), ÅF = Åsta Fault. Shear Zones: NSZ = Ninian Shear Zone, BSZ = Brent Shear Zone, TSZ = Tampen Shear Zone, LSZ = Lomre Shear Zone, USZ = Utsira Shear Zone, HSZ = Hardangerfjord Shear Zone, KSZ = Karmøy Shear Zone, SSZ = Stavanger Shear Zone.

Fault, with the Hardangerfjord Shear Zone also situated south of and in the footwall of the Øygarden Shear Zone (Figures 3b and 4; Fazlikhani et al., 2017). Further south, the N-S to NE-SW striking Karmøy and Stavanger shear zones occur in the footwall of the Åsta Fault and beneath the Stavanger Platform, respectively (Figures 3c and 4; Bøe et al., 2010; Phillips et al., 2016; Thon, 1980). The east dipping Utsira Shear Zone tracks the western margin of the Stord Basin (Figures 3b and 4; Fazlikhani et al., 2017; Fossen et al., 2016), and is represented by a series of shallowly east dipping to subhorizontal splays beneath the Utsira High (Figure 3c).

Reflections that may be related to the presence of deeply buried sediments can be identified beneath the Base RP1 surface (Figure 3). Coherent reflectivity beneath the Base RP1 surface across the Horda Platform may be

related to Caledonian basement allochthons, as drilled by well 31/6-1 (Fossen et al., 2016), or in some areas may represent sedimentary strata (Figures 3a and 4). Further coherent reflectivity beneath the Base RP1 surface is identified beneath the East Shetland Platform which, based on well information, is interpreted as Devonian sedimentary strata (Figure 3b; Patruno & Reid, 2016; Patruno et al., 2019). Reflectivity beneath the Base RP1 surface in the Ling Depression is interpreted to correspond to sediments deposited during late Carboniferous-Permian extension, which affected only the southern margin of the study area, although some Devonian strata may also be present locally (Heeremans et al., 2004; Heeremans & Faleide, 2004; Jackson & Lewis, 2016; Neumann et al., 2004).

5. Present-day Physiography of the Northern North Sea Rift

The Base RP1 surface records the cumulative effects of RP1 and RP2 basement-involved fault activity and defines a ~200 km-wide, predominately N-S oriented rift, bordered by the East Shetland Platform to the west and the Norwegian mainland to the east (Figure 4). The western margin to the rift is here termed the Western Boundary Fault (Figures 3 and 4), whereas the Øygarden and Åsta faults form the eastern rift margin south of the Måløy Slope (Figures 3c and 4). No rift-bounding fault is present across the Måløy Slope itself (Figure 4). The N-S to NNE-SSW striking Viking and Sogn grabens define the axis of the basin, with the Viking Graben comprising three segments, the South, Central, and North (Figure 4).

In the northwest of the study area, the ~80 km-wide East Shetland Basin contains numerous N-S to NE-SW striking, E to SE dipping normal faults. The depth to the Base RP1 surface in the East Shetland Basin ranges from 3 to 5 s TWT (~4–7 km; Figures 3a and 4). To the north, the Base RP1 surface deepens to 6–7 s TWT (~11 km) across the NE-SW striking Marulk and Magnus basins (Figure 4). East of the East Shetland Basin, the NNE-SSW striking North Viking Graben reaches a depth of 6 s TWT (~9 km) along its western margin, and to the northeast, the N-S striking Sogn Graben reaches ~8 s TWT (~12 km) and may deepen further to the north (Figure 4). East of the North Viking and Sogn grabens, the Måløy Slope is characterized by relatively minor (~100ms TWT (~200 m) throw) west and east dipping faults (Figure 4; Færseth et al., 1995; Lenhart et al., 2019; Reeve et al., 2015).

The Horda Platform is located along the eastern margin of the northern North Sea rift, south of the Måløy Slope and Lomre Shear Zone, and north of the Åsta Graben (Figure 4). This area encompasses the Stord Basin in the south and the Northern Horda Platform in the north. Its western margin is formed by the Oseberg Fault Block in the north and the Utsira High further south. The Brage Horst forms a N-S striking high to the east of the Oseberg Fault Block (Figure 4). The Northern Horda Platform is dominated by the N-S striking, west dipping Tusse, Vette, and Øygarden faults (Figure 4). Each of these faults displace the Base RP1 surface by ~1 s TWT (~1.5 km; Duffy et al., 2015; Whipp et al., 2014; Figure 3a). The depth to the Base RP1 surface across the Northern Horda Platform ranges from 3 to 4 s TWT (~4–7 km). The Vette Fault takes a prominent bend midway along its length where it strikes E-W and dips to the north. This bend corresponds to a "domain boundary" of Fossen et al. (2016) that correlates with the subcrop of the Lomre Shear Zone (Figure 4; Fazlikhani et al., 2017).

The Utsira High represents a major intrabasin high where the Base RP1 surface is at ~1.8 s TWT (~3 km) depth. Northeast dipping faults define the intrahigh Augvald Graben (Olsen et al., 2017). East dipping faults separate the Utsira High from the Stord Basin to the east (Figure 4), which, apart from the west dipping Øygarden Fault along its eastern margin, is dominated by east dipping faults (Figure 3b). The Øygarden Fault strikes N-S in the north, changing to NE-SW at the southern end of the Stord Basin. The east dipping fault along the western margin of the Stord Basin margin generally strikes N-S, but changes to strike NE-SW in the north (Figure 4).

In the N-S to NNE-SSW striking Central segment of the Viking Graben, the Base RP1 surface reaches a maximum depth of ~7 s TWT (~11 km) and in the Southern segment of the Viking Graben it reaches depths of ~4 s TWT (~6 km). Along the eastern margin of the Viking Graben, the Beryl Embayment separates the Southern and Central segments (Figure 4).

In the southeast of the study area, the NE-SW striking Ling Depression separates the Utsira and Sele highs. Further east, the Åsta Fault is separated from the Øygarden Fault by an ~60 km-wide relay ramp (Figure 4). Zechstein Supergroup evaporites are also present across the south of the study area, thinning northward in

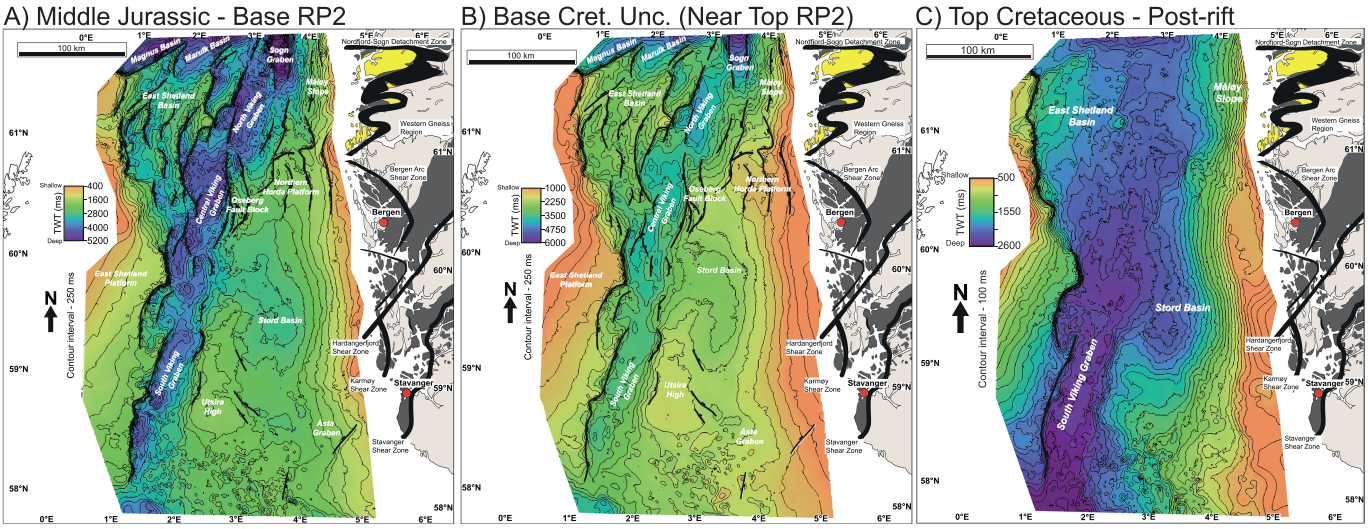

Figure 5. TWT structure maps of shallower structural levels across the northern North Sea rift, see Figures 2 and 3 for equivalent stratigraphic horizons. (a) TWT structure map of the Middle Jurassic (Base RP2) surface. The main structural lows are the South, Central, and North Viking Graben and the Sogn Graben, deepening to the north. (b) TWT structure map of the Base Cretaceous Unconformity (Near Top-RP2), showing the main structural lows in the Viking Graben. Note the additional low centered above the Stord Basin. (c) TWT structure map of the Top Cretaceous (Post-rift) surface. This surface shows little faulting aside from the Western Boundary Fault along its western margin and is dominated by a north trending depression, which widens northward.

the South Viking and Åsta grabens, and thickening into the Ling Depression and Norwegian-Danish Basin. Halite-poor and largely immobile parts of the evaporite sequence are present across the Utsira High, whereas a relatively thicker and halite-rich and thus more mobile salt is present across the Sele High (Figure 3c; Olsen et al., 2017; Sorento et al., 2018).

The present-day rift physiography at the Base RP2 and shallower depths differs to that of the Base RP1 surface. At these levels, the physiography of the Near Top-RP2 (BCU) surface largely mirrors that of Base RP2, albeit at shallower depths. The rift displays an overall deepening to the north, with the Viking and Sogn grabens forming the dominant structural elements, and the Marulk and Magnus basins also representing prominent features (Figures 5a and 5b). Faults are expressed across the Northern Horda Platform (Figure 3a), but there are notably few faults expressed in the Stord Basin, which forms an ~80 km-wide depression, and the Utsira High (Figures 3b, 5a, and 5b). The South Viking Graben forms a narrow (~40 km wide) rift which begins to widen northward along the western margin of the Oseberg Fault Block (Figure 5). Further north, Base RP2 and Near Top-RP2 surfaces describe a single wide rift from the East Shetland Basin to the Northern Horda Platform and Måløy Slope (Figure 5).

There is very little expression of faulting present across the Post-rift surface (Figures 3 and 5c), with only the rift-bounding Western Boundary Fault expressed at this level. As at the Base RP2 and Near Top-RP2 surfaces, the rift forms a narrow depression (~55–60 km wide) across the South Viking Graben, which widens northward to ~200 km across the East Shetland Basin and Måløy Slope (Figure 5c). In contrast to underlying surfaces, the deepest point of this surface (~2.6 s TWT; ~3 km) is located above the South Viking Graben rather than in the north (Figure 5c).

6. Rift Phase 1: Late Permian-Early Triassic

Rift Phase 1 depocenters predominantly trend N-S to NE-SW, are located within the hanging walls of N-S to NE-SW striking normal faults, and are widely distributed across the northern North Sea rift (Figure 6). The width of the rift during RP1 is relatively uniform from north to south, with fault activity distributed across a 170-km-wide zone from the East Shetland Basin to Northern Horda Platform in the north, and a 190-km-wide zone from the South Viking Graben to the Åsta Graben in the south. However, in the south, fault activity is localized in the South Viking Graben and Stord Basin rift segments, separated by the relatively unfaulted Utsira High (Figure 6). RP1 strata are notably thin atop the Utsira High, although a ~250 ms (~400 m) thick

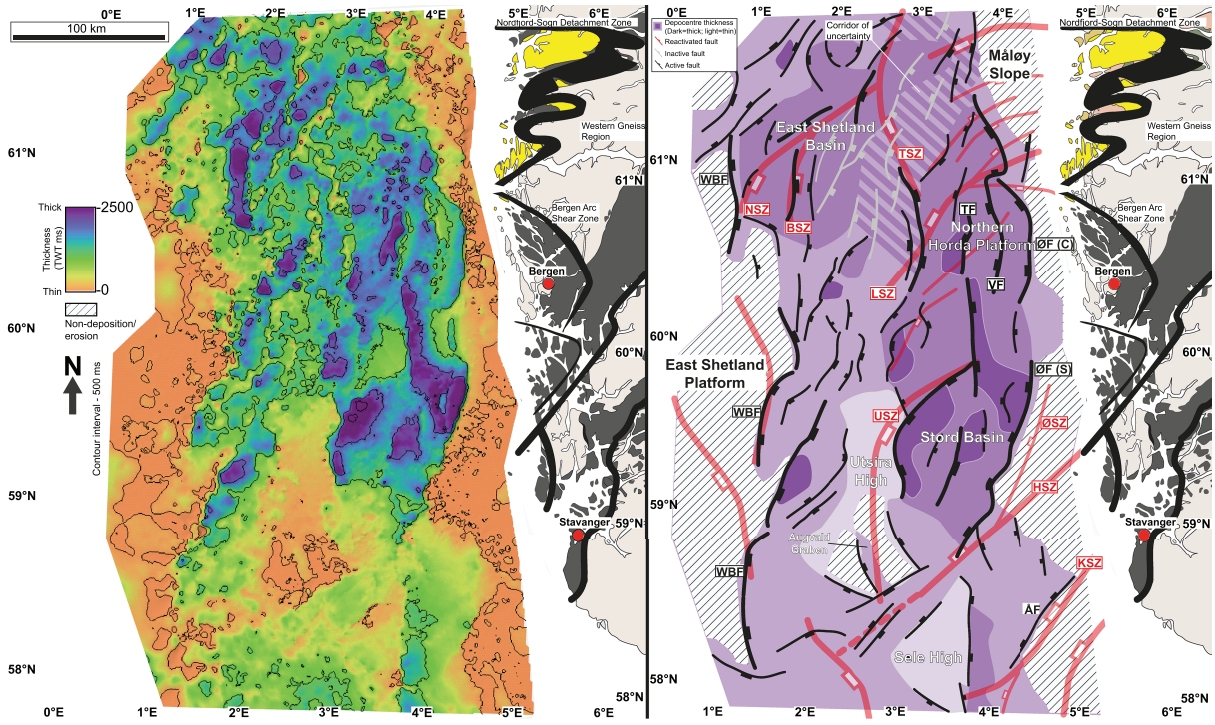

Figure 6. Time-thickness map for Rift Phase 1, calculated between the Base RP1 and Base RP2 surfaces. Calculated depocenters are shown on the left and interpretation on the right. Red lines show the location of the offshore extensions of major Devonian structures (after Fazlikhani et al., 2017). NSZ = Ninian Shear Z one, BSZ = Brent Shear Zone, TSZ = Tampen Shear Zone, LSZ = Lomre Shear Zone, USZ = Utsira Shear Zone, ØSZ = Øygarden Shear Zone, HSZ = Hardangerfjord Shear Zone, KSZ = Karmøy Shear Zone, WBF = Western Boundary Fault, TF = Tusse Fault, VF = Vette Fault, ØF (C and S) = Øygarden Fault (Central and Southern), ÅF = Åsta Fault.

interval is preserved within the NW-SE striking Augvald Graben. A condensed succession of RP1 strata (100–400-ms TWT; 200–600 m) occurs across the Sele High. No RP1 strata are preserved on platform areas outside of the main rift (Figure 6).

The main depocenters during RP1 were located in the Stord Basin and Northern Horda Platform along the eastern side of the rift (Figures 6–8), and the East Shetland Basin in the west (Figures 6 and 9), each containing up to 3,200 ms TWT (~4 km) of RP1 strata. Several internal depocenters were present in the Stord Basin, the largest of which, located within the hanging wall of the east dipping fault along the western basin margin, strikes N-S in the south and swings to trend NE-SW further north, paralleling the strike of the underlying Utsira Shear Zone (Figure 6). In cross section, the east dipping faults within the Stord Basin appear to root downward into the Utsira Shear zone (Figure 7). In a similar manner, the west dipping Øygarden fault along the eastern margin of the Stord Basin soles onto the underlying Øygarden and Hardangerfjord shear zones (Figures 4 and 7). A half-graben in the hanging wall of the Øygarden Fault displays clear syn-rift divergent wedges, confirming activity at this time (Figure 7). This N-S striking depocenter (2,000–2,500 ms TWT; ~5 km thick) swings to strike NNE-SSW to the south where the fault strikes parallel to the Hardangerfjord Shear Zone (Figures 6 and 7). To the southwest, along-strike of the Hardangerfjord Shear Zone, RP1 strata thicken into the bounding faults of the Ling Depression, which forms a NE-SW striking depocenter containing 800 ms TWT (~1.4 km) of RP1 strata (Figure 3c). To the east, the Åsta Graben also represents an RP1 depocenter containing ~700 ms TWT (~1.2 km) thick of RP1 strata (Figure 6).

North of the Stord Basin, a N-S striking depocenter (up to ~2,500 ms TWT; ~5 km thick) occurs in the hanging wall of an east dipping fault southwest of the Vette Fault (Figure 6). Across the Northern Horda Platform, the Tusse, Vette, and Øygarden faults form N-S striking half graben containing divergent syn-rift wedges (Figures 6 and 8). Further north, no RP1 strata are preserved on the Måløy Slope (Figure 6).

On the northeast side of the rift, the East Shetland Basin contains multiple depocenters (up to ~2,500 ms TWT; ~5 km thick) in the hanging walls of east dipping faults (e.g., the Tern, Ninian, and Brent faults), as well as the west dipping Eider Fault (Figures 3a and 9). The geometry of these depocenters parallels the

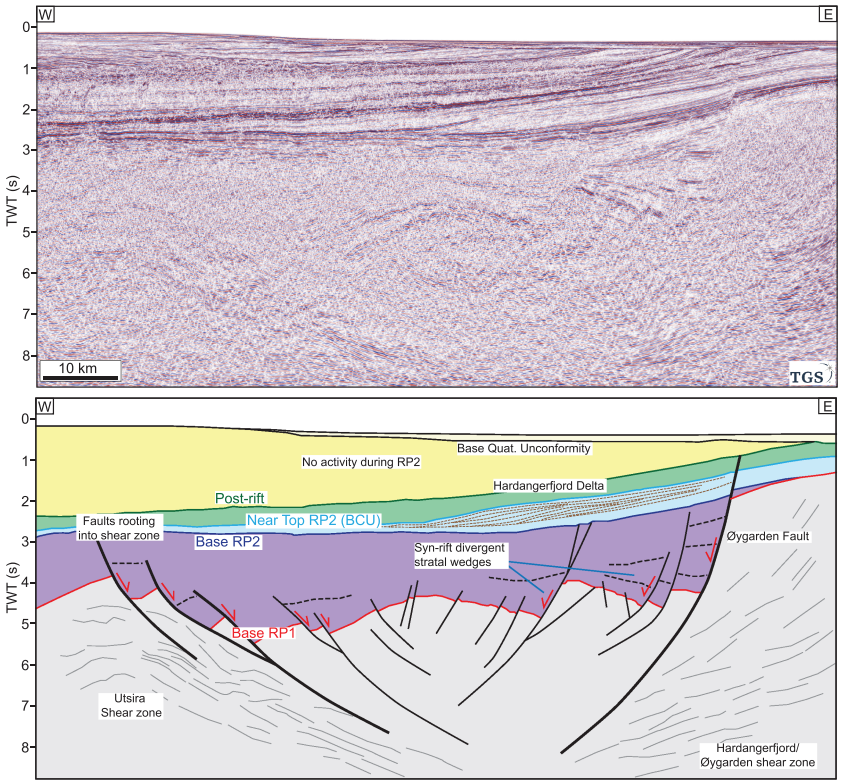

Figure 7. Uninterpreted and interpreted seismic section across the Stord Basin, see Figure 4 for location. The section shows major RP1 activity along basin-bounding faults, which appear to root down onto the underlying Utsira and Øygarden/Hardangerfjord Shear zones at depth. Westward progradation of the Hardangerfjord Delta can be observed in the RP2 interval. Data courtesy of TGS (NSR06-31158.0016678).

underlying Ninian, Brent, and Tampen shear zones, and the border faults to these depocenters also appear to merge together at depth, potentially linking with the underlying shear zones (Figures 6 and 9; Fazlikhani et al., 2017). North of the East Shetland Basin, the Marulk and Magnus Basins represent NE-SW striking depocenters containing up to 2,000 ms TWT (~5 km) of RP1 strata.

South of the East Shetland Basin, the Central and South Viking graben segments contain ~2,000 ms TWT (~5 km) and ~1,500 ms TWT (~3 km) of RP1 strata, respectively. Rift Phase 1 activity appears subdued across the North Viking and Sogn Grabens (Figure 6). However, as we are unable to resolve the Base RP1 surface accurately in the data used in these areas, the magnitude of the RP1 depocenters is uncertain and our interpretation represents a minimum estimate of RP1 thickness (Figure 6). As a result, we cannot be certain that the observed depocenter beneath the Northern Horda Platform does not extend westward and merge with that of the East Shetland Basin (Figures 6 and 9). Observations from the East Shetland Basin suggest a regional thickening of Triassic strata toward the east (Figure 9), perhaps indicating that the depocenters may well merge beneath the North Viking Graben.

7. Rift Phase 2: Late Jurassic-Early Cretaceous

The time-thickness map calculated for RP2, between the Base RP2 and Near Top RP2 surfaces, records the majority of syn-rift activity associated with Late Jurassic-Early Cretaceous rifting (Figures 3 and 10). The distribution of fault activity during RP2 differed to that of RP1 (Figure 10). The most notable feature of the RP2 time-thickness map is that fault activity is focused along the Viking and Sogn grabens (Figure 10) and not in the Stord Basin and Northern Horda Platform (Figure 6). Rift activity in the south is localized along the ~25 km wide South Viking Graben, between the East Shetland Platform in the west and the Utsira High to the east (Figure 7). No RP2 activity is evident in the Stord Basin (Figures 7 and 10). Rift activity widens northward, with faults active across the Oseberg Fault Block and Brage Horst (Figure 10; Færseth

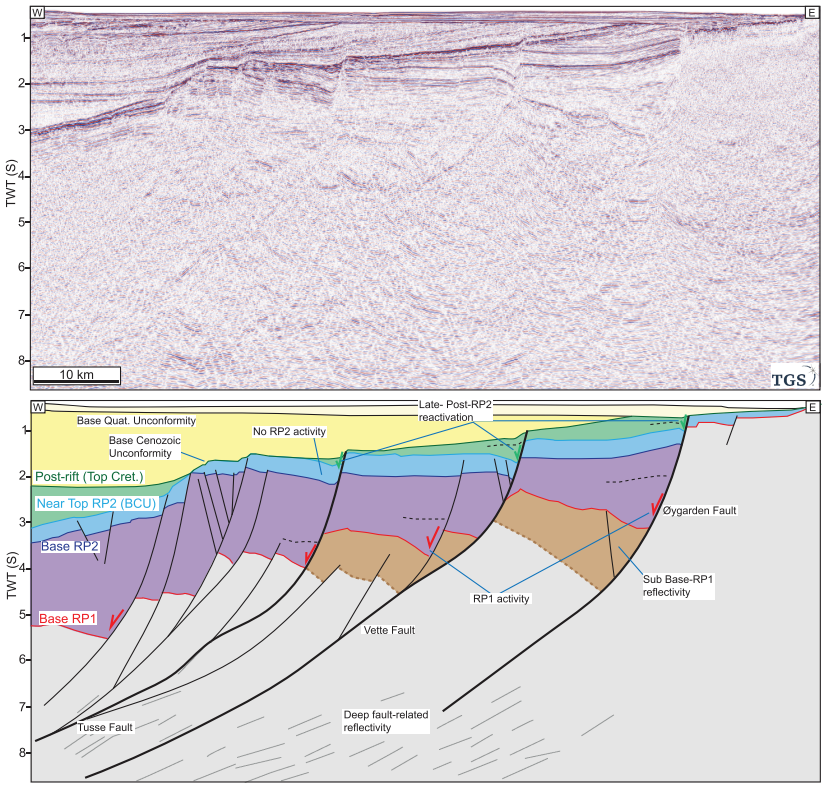

Figure 8. Uninterpreted and interpreted seismic section across the Northern Horda Platform, see Figure 4 for location. The west dipping Tusse, Vette, and Øygarden Faults show activity in the Triassic (RP1) and Cretaceous (Late-syn- to Post-RP2) with no activity in the Late Jurassic (RP2). The Øygarden and Vette Faults also show evidence of reflectivity below the Base RP1 surface. Data courtesy of TGS (NSR06-31182.0009614).

& Ravnås, 1998). Further north, a ~700 ms TWT (~1.2 km) depocenter occurs in the hanging wall of the bend in the Vette Fault. In the north of the study area, fault activity was distributed over roughly the same area as in RP1 (~190 km), with activity widening in the east onto the Måløy Slope (Figures 3a and 10). The eastern boundary to the active rift during RP2 appears to follow the Utsira High in the south and the Lomre Shear Zone further north, with no activity observed east of this boundary (Figure 10).

The Viking Graben forms the main depocenter during RP2; individual depocenters, including the South, Central, and Northern segments and the Sogn Graben, contain syn-rift divergent wedges, strike N-S, and have a right stepping relationship to one another (Figures 3 and 5). RP2 thicknesses reach 1,350 ms TWT (~2.5 km) in the South Viking Graben and 1,000 ms TWT (~2 km) in the Central Viking Graben, increasing to ~1,800 ms TWT (~3.2 km) in the Sogn Graben (Figure 10). In the north, the NE-SW striking Magnus Basin was a major depocenter during RP2, containing ~700 ms TWT (~1.2 km) of strata. RP1 faults within the East Shetland Basin were also reactivated during RP2. The Tern, Eider, Osprey, Brent, and Murchison faults each contain RP2 syn-rift divergent wedges (up to ~500 ms TWT; ~1 km thick) in their hanging walls (Figures 3a and 9; Claringbould et al., 2017). The thickness of RP2 strata is reduced in certain areas of the East Shetland Basin, particularly in the immediate footwalls of faults, where RP2 strata are often absent due to erosion by the BCU (Figure 9).

Rift Phase 2 strata are mostly isopachous across the Northern Horda Platform (~400 ms TWT; 750 m thick) with no syn-rift divergent wedges observed in the hanging walls of the Tusse, Vette, and Øygarden Faults (Figures 8 and 10). To the west, faults across the Oseberg Fault Block and along the eastern margin of the Brage Horst were active during RP2, with depocenters containing thicknesses of up to 500 ms TWT (~1 km; Figures 3a and 10; Færseth & Ravnås, 1998). The ~800 ms TWT (~1.5 km) sedimentary thicknesses in the Stord Basin and Northern Horda Platform have a broad lobate planform geometry. The presence of clinoform sequences within these lobate intervals suggests that the lobate area represents the progradation of the Hardangerfjord and Sognefjord deltaic systems into accommodation not generated through fault-controlled

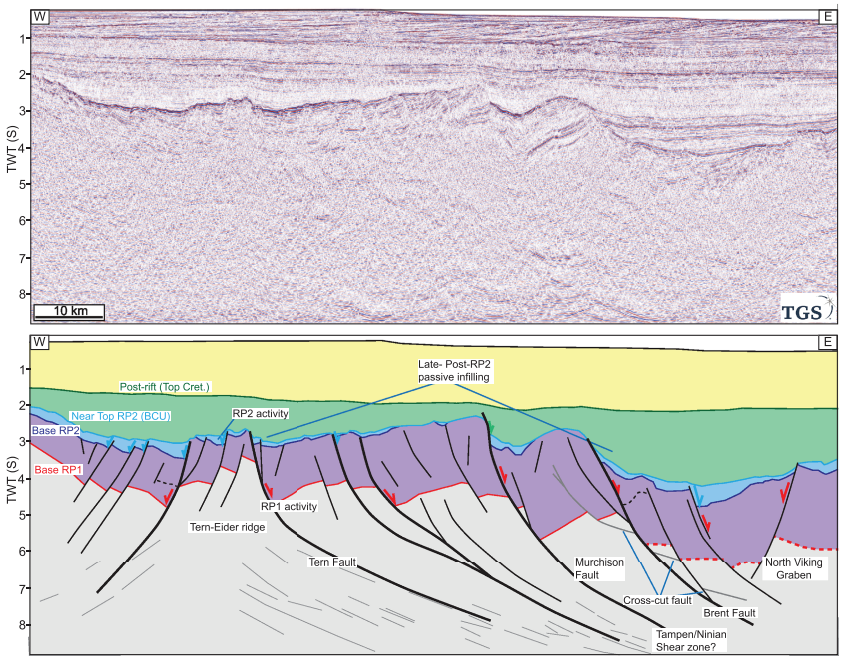

Figure 9. Uninterpreted and interpreted section from across the East Shetland Basin, see Figure 4 for location. East dipping faults appear to merge beneath the East Shetland Basin and may link to the Tampen and Ninian shear zones in this area. The depth to the Base RP1 surface becomes uncertain to the east beneath the North Viking Graben. Data courtesy of TGS (NSR06-21188.0010680)

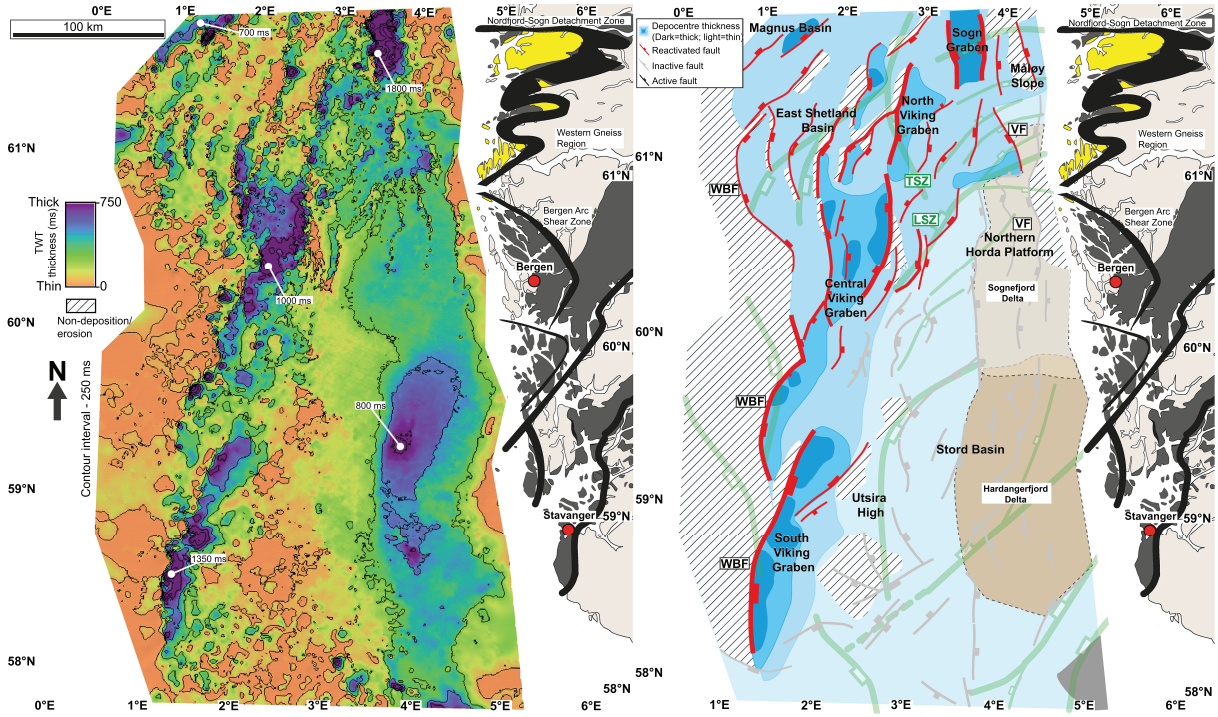

Figure 10. Time-thickness and activity maps for RP2, calculated between the Base RP2 and BCU (Near Top-RP2) surfaces. Dashed diagonal lines correspond to areas of nondeposition or erosion. Green lines represent the offshore location of Devonian shear zones, with structures referred to in the text labeled. The Upper Jurassic Hardangerfjord and Sognefjord deltaic sequences are shown in brown. TSZ = Tampen Shear Zone, LSZ = Lomre Shear Zone, WBF = Western Boundary Fault, VF = Vette Fault.

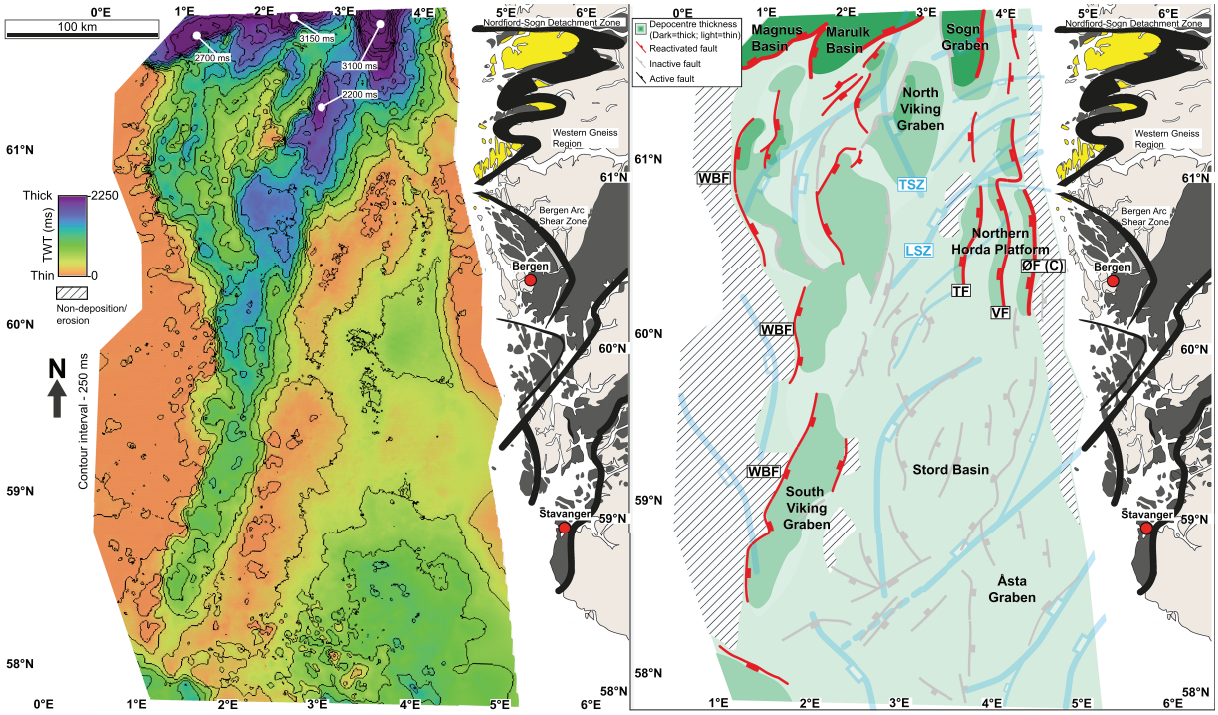

Figure 11. Time-thickness map for Late-syn- to Post-RP2, calculated between the BCU (Near Top-RP2) and top Cretaceous (Post-rift) surfaces. Devonian shear zones are highlighted by light blue lines. The thickness of strata increases northward into the Sogn Graben and Marulk and Magnus Basins. Note the reactivation of the faults across the Northern Horda Platform. TSZ = Tampen Shear Zone, LSZ = Lomre Shear Zone, WBF = Western Boundary Fault, TF = Tusse Fault, VF = Vette Fault, ØF (C) = Øygarden Fault (Central).

subsidence (Figures 3b, 7, and 10; Dreyer et al., 2005; Ravnås & Bondevik, 1997; Ravnås et al., 2000; Sømme et al., 2013). South of the Hardangerfjord Delta, although a thickness change of ~200 ms TWT (~300 m) occurs across the Åsta Fault, no growth strata are present in the hanging wall, indicating a lack of tectonic activity on the Åsta Fault at this time (Figures 3c and 10). As with RP1, RP2 strata are thin across most of the Utsira High.

8. Late-Syn-Rift- to Post-Rift Phase 2: Cretaceous

The late-syn-rift to post-RP2 time-thickness map (termed Late-syn- to Post-RP2), calculated between the BCU and the Post-rift surface, encompasses the entire Cretaceous interval and largely comprises a thick post-RP2 succession, although some relatively thin intervals of late RP2 syn-rift strata are present locally (Figure 9). A large, relatively isopachous unit typically forms the upper part of the Cretaceous interval, for example, across the East Shetland Basin and Sogn Graben (Figures 9 and 12), indicating widespread thermal subsidence in these areas post-RP2. Divergent stratal wedges are identified locally in the lower parts of the interval, indicating some syn-rift activity at this time (Figures 8 and 9).

The distribution of depocenters across the Late-syn- to Post-RP2 time-thickness map is broadly similar to that recorded during RP2 (i.e., Base RP2 to Near Top-RP2; Figure 11). The overall thickness of Late-syn- to Post-RP2 strata increases northward, from ~950 ms TWT (~1.6 km) in the South Viking Graben to >3 s TWT (>5 km) in the Marulk and Magnus basins and the Sogn Graben (Figure 11). Late-syn- to Post-RP2 strata thin toward the south (<500 ms TWT; <800 m), with a thin interval present in the Stord Basin (Figure 7). The base of individual depocenters appear flatter than those identified in RP1 and RP2, and internally, the stratigraphy displays less pronounced thickening toward bounding faults (Figure 11). This indicates a lack of fault activity at this time and a predominance of postrift thermal subsidence with, in some cases, the passive infilling of remnant relief related to earlier phases of rifting (Prosser, 1993).

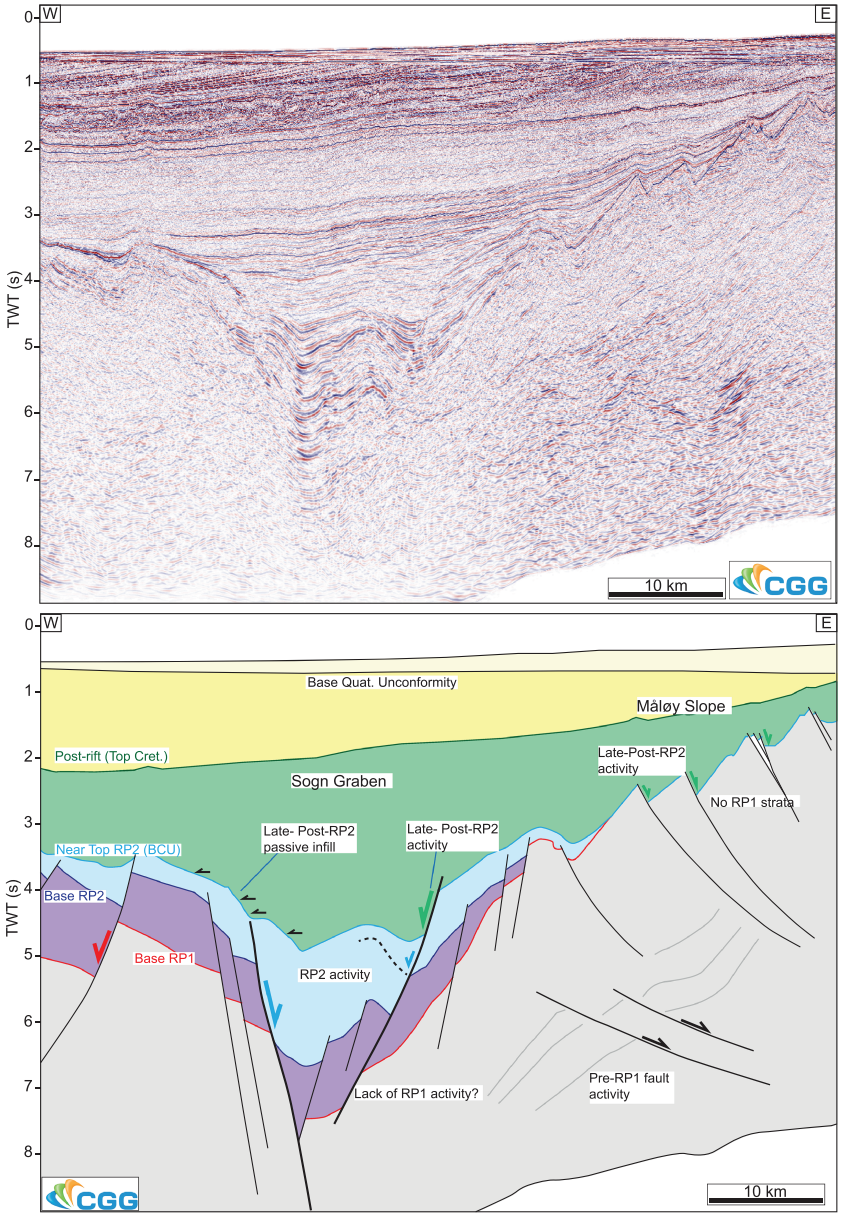

Figure 12. Uninterpreted and interpreted seismic sections across the Sogn Graben, see Figure 4 for location. The Sogn Graben displays some activity during RP1 but is mainly active in RP2. The eastern margin of the graben is active during RP2 and Late-syn- to Post-RP2 intervals. No RP1 strata are present across the Måløy Slope, which shows RP2 activity. Data courtesy of CGG (Horda Platform Broadband 3-D seismic volume).

In the south, the South Viking Graben depocenter is bordered to the east by the Utsira High, where Late-syn- to Post-RP2 strata are thin and locally absent (typically <150-ms TWT; <200 m; Figures 10 and 11). As in RP2, east of the Utsira High, no Late-syn- to Post-RP2 activity is recorded across the Stord Basin and Åsta Graben. Nevertheless, these areas contain 700–900-ms TWT (~1.2 km) of Late-syn- to Post-RP2 strata, likely deposited in accommodation related to post-RP1 thermal subsidence, as no RP2 activity occurred in this area (Figure 11). However, on the Northern Horda Platform, depocenters in the hanging walls of the Tusse, Vette, and Øygarden Faults contain up to ~600 ms TWT (~1 km) of Late-syn- to Post-RP2 strata. The majority of this strata forms syn-rift divergent wedges (Figures 8 and 11), indicating late-to-post RP2 reactivation of these faults (Bell et al., 2014). Late-syn- to Post-RP2 strata in the hanging wall of the Øygarden Fault are

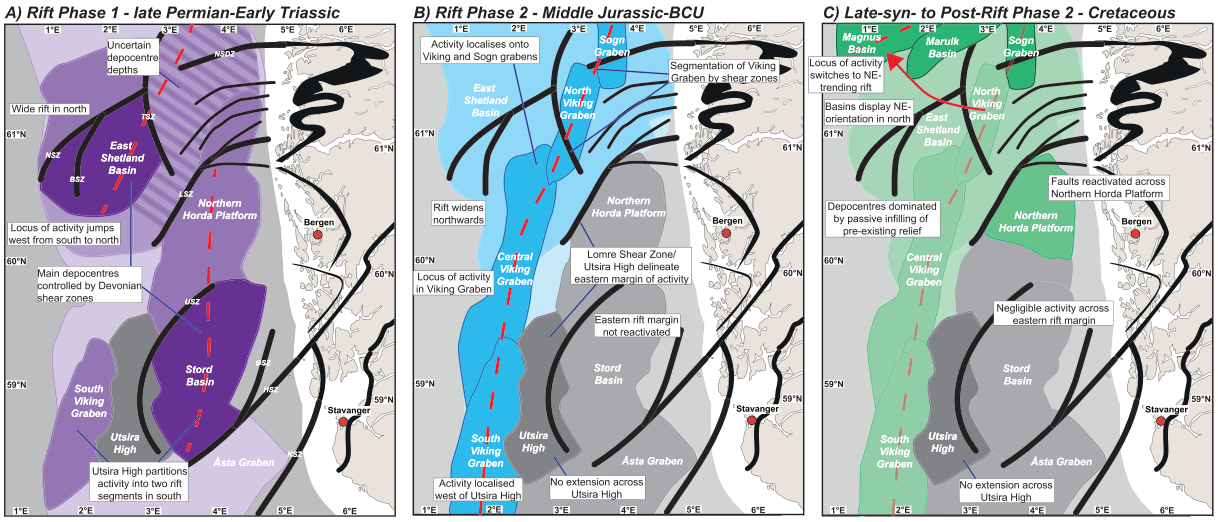

Figure 13. Regional model for the multiphase evolution of the northern North Sea rift. (a) Major RP1 depocenters in the Stord Basin and East Shetland Basin are delineated by and somewhat controlled by the Devonian shear zones. (b) RP2 activity localizes onto the Viking and Sogn Grabens and the East Shetland Basin, with negligible activity observed across the Stord Basin and Northern Horda Platform, east of the Utsira High and the Lomre Shear Zone. (c) Rift activity migrates northward during the later stages and following RP2. Activity occurs along the NE trending Marulk and Magnus Basins in the north of the area with local flexure related reactivation of faults across the Northern Horda Platform.

truncated by the overlying Base Cenozoic unconformity (equivalent to the Top Cretaceous) and therefore do not record the true depositional thickness (Figure 8).

Depocenters in the East Shetland Basin strike N-S in the south, swinging round to NE-SW further north (Figure 11). These depocenters contain 900–1,300 ms TWT (1.6–2.3 km) of Late-syn- to Post-RP2 strata. These depocenters show limited thickening into the hanging wall of faults (with the Murchison Fault being an exception; Figure 9) and are typically characterized by subhorizontal Cretaceous strata that onlap onto rotated Jurassic strata (Figures 9 and 10), indicating a relative lack of fault activity in the East Shetland Basin at this time. We propose that these depocenters record passive filling of accommodation generated through Late Jurassic RP2 fault activity.

East of the East Shetland Basin, the Sogn Graben forms a large Late-syn- to Post-RP2 depocenter, containing >3 s TWT (~5 km) of Cretaceous strata (Figures 11 and 12). Syn-rift divergent wedges in the hanging wall of

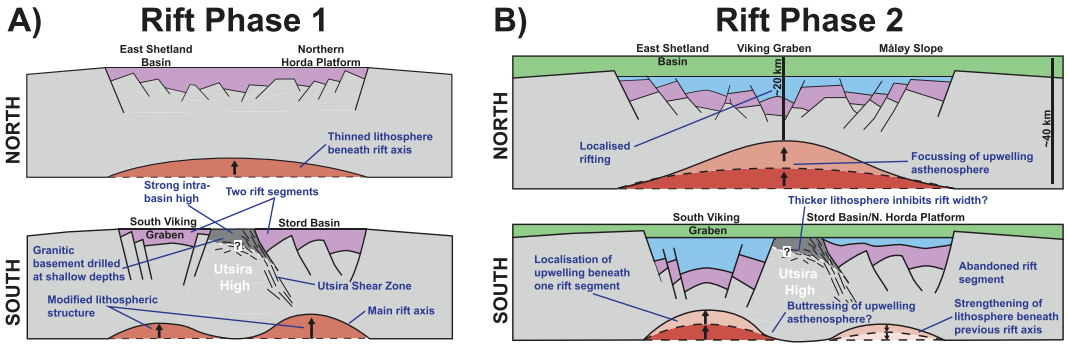

Figure 14. Schematic model illustrating the difference in activity between the northern and southern sections of the study area, and the role of the Utsira High. (a) During RP1, rift activity in the north is distributed over a wide area, forming a wide rift and resulting in uniform lithospheric thinning. In the south, extension is localized into two segments either side of the relatively unfaulted Utsira High, producing relatively thin lithosphere beneath the rift segments and leaving relatively thicker lithosphere beneath the Utsira High. Question marks reflect the uncertainty associated with the nature of basement at greater depths beneath the Utsira High. (b) During RP2, the uniformly thinned lithosphere in the north focuses activity toward the axis, creating a localized rift centered across the Viking Graben. Estimated crustal thicknesses in the northern model are taken from Christiansson et al. (2000). In the south, the modified lithospheric structure remnant from RP1 focuses activity along one rift segment, the South Viking Graben, buttressed by the thicker lithosphere of the Utsira High, while the rift segment on the opposite side to the Utsira High, the Stord Basin, becomes abandoned.

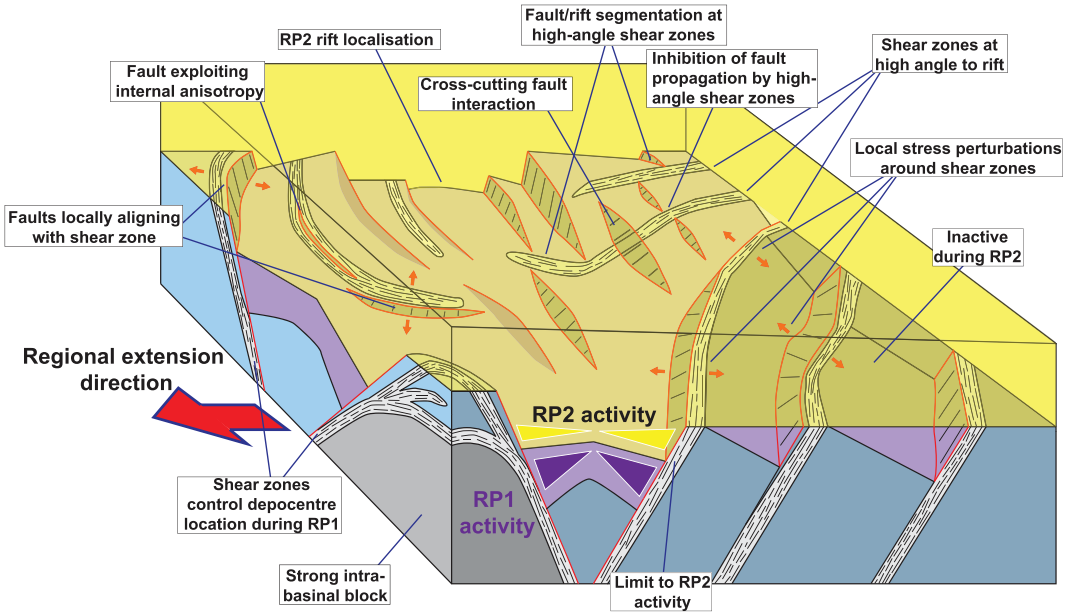

Figure 15. The 3-D box model highlighting the range of possible interactions between preexisting basement structures and rift related faults throughout multiple rift phases. Shear zones may locally perturb the regional stress field, causing incipient faults to locally align along these structures. Faults may also exploit internal anisotropies within shear zones, or where the shear zones are oriented at a relatively high angle, be segmented by them. In some instances, shear zones may form the limit to activity during later rift events. Strong, potentially granite-cored, intra-basinal highs are often located in the footwalls of faults and are typically resistant to extension.

the eastern border fault of the Sogn Graben indicate that this structure was active during RP2 and the early stages of Late-Post RP2 (Figure 12). Faults along the western side of the Sogn Graben were active during RP2, but became inactive with their hanging walls being passively filled during Late-syn- to Post-RP2 (Figure 12).

The generation of the accommodation for the upper postrift strata in the Late-syn- to Post-RP2 interval appears to be related to thermal subsidence following RP2 activity (Figure 11), as evidenced by the large thicknesses present in the South and Central Viking grabens (Figures 3b and 3c). The thickness of Late-syn- to Post-RP2 strata is locally accentuated by fault activity in the Sogn Graben and Marulk and Magnus Basins, and local westerly tilting in the north of the study area (Figures 11 and 12; Brekke & Riis, 1987). The increased thickness of Late-syn- to Post-RP2 strata in the north of the study area reflects a relative increase in activity related to proto-North Atlantic opening in the Møre Basin–Faroe-Shetland Basin–Rockall Trough axis to the north of the study area (Kristoffersen, 1978; Roberts et al., 1999), which is related to a decrease in rift activity in the northern North Sea. The NE-SW striking Marulk and Magnus Basins are aligned with the Atlantic rifts and Møre-Trondelag Fault Complex, reflecting this northward migration of activity (Figures 11 and 13; Dore et al., 1997; Gabrielsen et al., 2001).

9. Discussion

We have explored the kinematic and geometric evolution of the northern North Sea rift throughout late Permian-Early Triassic (RP1) and Late Jurassic-Early Cretaceous (RP2) rift phases (Figure 13). Drawing on these observations, and those from other rift systems worldwide, we first discuss how preexisting structures influence the initial rift physiography, before examining how the rift physiography and kinematics evolve during multiple phases of rifting.

9.1. Reactivation and Inheritance of Basement Shear Zones During Rifting

Basement shear zones display a range of strikes beneath the northern North Sea rift (Figure 4). Numerical modeling, along with previous studies from the North Sea show that shear zones that strike within 45–90° of the regional extension direction, that is, close to perpendicular, and have dips greater than 30° are able to influence fault strike during rifting. Rift-related faults often align in map view

with shear zones displaying these characteristics (Bird et al., 2014; Deng, Gawthorpe, et al., 2017; Fazlikhani et al., 2017; Phillips et al., 2016). In the northern North Sea, the Åsta Fault strikes parallel to the offshore continuation of the Karmøy Shear Zone, while the Ling Depression parallels the offshore continuation of the Hardangerfjord Shear Zone (Fazlikhani et al., 2017; Fossen & Hurich, 2005; Phillips et al., 2016). Similarly, the dominant N-S to NE-SW strike of faults in the East Shetland Basin parallels the underlying N-S to NE-SW striking Tampen, Brent, and Ninian shear zones (Figures 4, 6, and 13). However, in areas such as the Måløy Slope, shear zones strike subparallel to the interpreted E-W oriented regional stress field and are therefore oriented at high angles to rift-related faults, bearing little influence over their strike (Figure 13).

There are multiple geometric and kinematic interactions between basement shear zones and rift-related faults. Rift-related faults have previously been shown to exploit internal mylonitic layers within shear zones (Gontijo-Pascutti et al., 2010; Heilman et al., 2019; Kirkpatrick et al., 2013; Morley, 2017; Paton & Underhill, 2004; Salomon et al., 2015), with examples also documented from the northern North Sea rift (Figure 15; "exploitative" interaction of Fazlikhani et al. (2017) and Phillips et al. (2016)). Numerical and analog modeling has shown that rocks containing a fabric are weaker, and thus more likely to fail, along said fabric when subject to favorably oriented stress fields (Chattopadhyay & Chakra, 2013; Tong & Yin, 2011; Youash, 1969; Zang & Stephansson, 2009).

Basement shear zones in the northern North Sea may also locally perturb the regional stress field, causing nearby or newly formed faults to locally align with the preexisting structure rather than perpendicular to the extension direction ("merging" interaction of Phillips et al. (2016); Figure 15). In the northern North Sea, the southern extension of the otherwise N-S striking Øygarden Fault rotates to a NE-SW orientation and locally aligns with the NE-SW striking Hardangerfjord Shear Zone, suggesting a local NE-SW oriented stress field associated with the shear zone (Figures 6 and 15). The Hardangerfjord shear zone represents a major structure across the northern North Sea rift and is associated with a Moho offset at depth (Gabrielsen et al., 2015; Maystrenko et al., 2017). Similarly, faults defining the western margin of the Stord Basin follow the underlying Utsira Shear Zone in plan-view, rotating from N-S in the south to NE-SW further north. These faults merging with the shear zone at depth (Fazlikhani et al., 2017; Figure 7). Instances where preexisting heterogeneities locally perturbed the regional stress field have also been interpreted in the East African Rift (Corti et al., 2007; Philippon et al., 2015), the Gippsland Basin offshore Australia (Samsu et al., 2019), the Taranaki Basin offshore New Zealand (Collanega et al., 2018), and Thailand (Morley, 2010, 2017). Although local faults may be misaligned with respect to the regional stress field, at the regional scale, overall rift kinematics do appear to be compatible with the extension direction (Corti et al., 2007; Philippon et al., 2015).

In contrast to the above interactions, where rift-related faults align with basement shear zones, E-W striking shear zones oriented subparallel to the extension direction do not directly influence fault strike. However, these high-angle shear zones are often associated with areas of changing structural style and segmentation at both the fault and rift scales (Figure 15). At the fault scale, high-angle structures may form boundaries to the lateral propagation of faults (e.g., Duffy et al., 2015; Nixon et al., 2014), or may transfer strain from one fault to another within a rift (Bladon et al., 2015; Mortimer et al., 2016). In the northern North Sea, we identify similar interactions, where the Lomre Shear Zone correlates to a 90° bend along the Vette Fault (Figure 6; Fazlikhani et al., 2017; Fossen et al., 2016; Lenhart et al., 2019), while the offshore corrugations of the Nordfjord-Sogn Detachment govern fault and rift architecture across the Måløy Slope (Lenhart et al., 2019).

At the rift scale, shear zones oriented at high angles to the rift may segment rift basins and control the geometry and distribution of depocenters (see also "Domain Boundaries" of Fossen et al. (2016)). Within the northern North Sea this is particularly important for the distribution of major depocenters during RP1 and the segmentation of the Viking/Sogn graben system during RP2. The Hardangerfjord Shear Zone separates the Stord Basin and Åsta Graben (Figure 10a). The Tampen Shear Zone coincides with the boundary between the North and Central Viking Graben (Figures 10 and 13a), while further north, Smethurst (2000) identifies two NW-SE striking lineaments which bisect the North Viking and Sogn grabens. Furthermore, the southern continuation of the Lomre Shear Zone projects between the South and Central Viking grabens and toward the Beryl Embayment (Figures 10 and 13b). These structures

oriented at high angles to the rift appear to constrain the length of each rift segment and thus segment the overall rift.

Potential mechanisms for this rift segmentation may include local stress perturbations surrounding the high-angle structures, as observed in the Turkana depression of the East African rift (Brune et al., 2017), or the inhibition or retardation of faults at these high-angle structures, as observed offshore West Greenland (Peace et al., 2017) and along the Atlantic rifted margins (Koopmann et al., 2014). Where they strike at 45–90° to the regional stress field, Devonian shear zones delineate the main depocenters during RP1. The Utsira and Hardangerfjord shear zones delineate the main Stord Basin depocenter (Figures 7 and 13), while the Tampen, Brent, and Ninian shear zones align with and delineate the main depocenters in the East Shetland Basin (Figures 9 and 13). Areas underlain by high-angle shear zones (oriented 0–45° to the regional extension direction), such as the Viking Graben and Måløy Slope form less major depocenters during RP1, with the rift-related faults often constrained or segmented by the preexisting structures (Figure 15). The presence of Devonian shear zones exerts a strong influence over the distribution and geometry of rift-related faults and therefore over depocenter geometry, at least during the initial stage of rifting (Figures 13 and 16).

The Lomre Shear Zone appears to represent a key structure throughout the evolution of the northern North Sea, corresponding to the location of strain transfer during RP1 between the Stord Basin along the eastern rift margin and the East Shetland Basin further north along the western margin, and delineating the eastern boundary to rift activity in RP2 (Figure 13). This structure has an enhanced influence throughout the multiphase evolution of the rift compared to other interpreted Devonian shear zones. One possibility is that the Lomre Shear Zone extends to greater (i.e., midcrustal) depths, or that it reactivates a Caledonian or earlier structure, both of which have been proposed for the Hardangerfjord Shear Zone further south, which also exerts a different influence over rift physiography, being associated with a Moho offset at depth and controlling the location and geometry of the rift-bounding faults in the Ling Depression (Fossen et al., 2014; Fossen & Hurich, 2005; Gabrielsen et al., 2015; Maystrenko et al., 2017). The Lomre Shear Zone has been proposed to represent the southern extension of the Nordfjord-Sogn Detachment by Færseth et al. (1995), although it does not appear to correlate with the structure onshore (Figure 4).

9.2. Strain Localization Around Structural Highs

The Utsira High forms a prominent intrabasin high within the northern North Sea that appears only weakly faulted throughout RP1 and RP2 (Figures 4 and 13). Multiple basement well penetrations across the Utsira High suggest that, at least in the upper few meters, crystalline basement is granitic (Fazlikhani et al., 2017; Lundmark et al., 2013; Riber et al., 2015; Slagstad et al., 2011). Granitic bodies typically have large density and rigidity contrasts with surrounding lithologies, and as such are often thought to resist extensional stresses and localize strain around their margins (Bott et al., 1958; Critchley, 1984; de Castro et al., 2007; Howell et al., 2019). The North Pennine and Lake District batholiths in northern England (Chadwick et al., 1989; Critchley, 1984; Evans et al., 1994; Howell et al., 2019; Kimbell et al., 2010), as well as granitic bodies interpreted beneath the North Sea (Donato et al., 1983; Donato & Tully, 1982; Lundmark et al., 2013) typically form structural highs and appear relatively unaffected by major faulting. Furthermore, at larger scales, numerical modeling has demonstrated that deformation may localize around the margins of areas of stronger material (Naliboff & Buiter, 2015; Pascal et al., 2002; Wenker & Beaumont, 2016), as observed with the localization of rifting in orogenic belts surrounding cratonic areas (Daly et al., 1989; Ebinger et al., 1997). The granitic basement beneath the Utsira High likely does not extend to great depths within the crust as it may be limited by the deeper Utsira Shear Zone (Figures 3b, 3c, and 14). It may be the case the that the Utsira High is uplifted and exhumed within the footwall of the Utsira Shear Zone in this area, similar to as observed in core complexes in the North Sea and Barents Sea (Henstra & Rotevatn, 2014; Koehl et al., 2018; Steltenpohl et al., 2004). In addition, strain may localize along the Utsira Shear Zone during rift activity rather than across the high itself. Regardless of the mechanism of its formation, the Utsira High represents a long-lived structural high that experienced little internal deformation during RP1 and RP2, and is underlain by granitic material at shallow basement depths.

We suggest that the presence of this granitic material at shallow basement depths beneath the Utsira High may inhibit fault nucleation across the structure during RP1. Strain localizes around the margins of the Utsira High, in the adjacent South Viking Graben and Stord Basin during RP1 and solely within

the South Viking Graben during RP2 (Figure 14). Further north, where such granitic material is either not present, or alternatively not uplifted in the footwall of a shear zone, strain is more uniformly distributed, forming a single, wide rift (Figures 6 and 14b). Although we are unable to directly image the crustal structure in this area to test this hypothesis, the 3-D crustal model of Maystrenko et al. (2017), although at a relatively coarse resolution, indicates thinned lithosphere beneath the Horda Platform and slightly thicker lithosphere beneath the Utsira High, in agreement with the model-driven hypotheses presented here.

9.3. Migration of Rift Activity During Multiphase Rifting

Rift physiography evolves during the multiphase evolution of the northern North Sea rift. Activity during RP1 is distributed over a wide area, forming a relatively uniform rift. Based on the position of the main depocenters, the main locus of rift activity passes through the Stord Basin and Northern Horda Platform along the eastern side of the rift, before switching to the western side at the Lomre Shear Zone and continuing northward through the East Shetland Basin (Figure 13).

During RP2, the location and magnitude of the major depocenters bears less correlation to the location of Devonian shear zones and rift activity instead localizes along the Viking and Sogn grabens, where crustal thickness is reduced to ~20 km (Figure 14; Christiansson et al., 2000). This suggests a decreasing influence from structural inheritance in controlling fault and depocenter geometry during RP2 (Figure 13). This diminishing influence of discrete basement structures may reflect an increasing thermal influence associated with the evolving thermal and rheological structure of the lithosphere. Progressive thinning of the lithosphere during extension is often associated with a narrowing of the overall rift system as upwelling asthenosphere is increasingly focused into a narrower area. This localization of lithospheric thinning and rift activity has previously been demonstrated across the north of the area (i.e., the East Shetland Basin and Northern Horda Platform) through the analysis of crustal-scale seismic sections (Christiansson et al., 2000; Odinsen et al., 2000). The increasing thermal effects following lithospheric thinning may cause new rift-related faults to largely ignore preexisting structural heterogeneities (Cowie et al., 2005; Odinsen et al., 2000; Paton et al., 2016; Ragon et al., 2018; Roberts et al., 1995). However, numerical modeling has also shown that, during multiphase rifting, the lithosphere beneath older rifts may strengthen during interrift periods and therefore be less prone to reactivation during later events (Naliboff & Buiter, 2015). Within the northern North Sea, we observe an overall localization of the rift system from RP1 to RP2, suggesting that there may not have been sufficient time between rift phases to sufficiently strengthen the lithosphere, or that extension was more protracted throughout RP1 and RP2. Observations from the East Shetland Basin and Oseberg Fault Block indicate that fault activity may continue, albeit at a reduced rate, in the interrift period between RP1 and RP2 (Claringbould et al., 2017; Deng, Fossen, et al., 2017). However, strengthening of the lithosphere beneath the RP1 axis in the Stord Basin may also have contributed to the lack of activity in this area during RP2 and the localization of activity in the adjacent South Viking Graben (Figure 14).

During its latter stages, and following RP2, tectonic activity migrated northward to the NE-SW trending Marulk and Magnus basins and the Sogn Graben, with little fault activity observed elsewhere (Figures 11 and 13). In addition, faults across the Northern Horda Platform that were not active during RP2, are active during Late-syn- to Post-RP2 (Figure 11). These faults were diachronously reactivated from west to east, with those in the west (i.e., toward the Oseberg Fault Block) potentially being active in the Late Jurassic (Bell et al., 2014). At this time, rift activity within the northern North Sea lessens and extension in the proto-North Atlantic to the north increases, resulting in a migration of rift activity northward and an increase in fault activity in the north of the northern North Sea rift (i.e., Marulk and Magnus Basins, Sogn Graben; Coward et al., 2003; Kristoffersen, 1978; Roberts et al., 1999).

Faults across the Northern Horda Platform are also reactivated during Late-syn- to Post-RP2, although this does not appear to be directly related to proto-North Atlantic extension in contrast to activity further north. Rather, Late-syn- to Post-RP2 reactivation of faults across the Northern Horda Platform is proposed to be related to flexural downbending occurring in response to the increase in tectonic activity to the north (Bell et al., 2014; Brekke & Riis, 1987). This suggests that activity across the Northern Horda Platform during Late-syn- to Post-RP2 was mainly related to local flexural stresses and that the eastern margin of the rift (east

of the Lomre Shear Zone and Utsira High) was only indirectly influenced by, and largely remained isolated from regional stresses post-RP1.

Although more localized during RP2, rift activity in the north of the study area occurs over roughly the same area in RP1 and RP2. However, in the south, rifting is localized in the South Viking Graben and Stord Basin during RP1 and solely the South Viking Graben during RP2, with little activity across the intervening Utsira High (Figure 14). Extension during RP2 was thought to be at least partly driven by stresses originating from the triple point of the trilete rift system of the Central, Witch Ground, and Viking grabens (Coward et al., 2003; Quirie et al., 2019; Rattey & Hayward, 1993; Underhill & Partington, 1993). Based on it its relative proximity to the origin of this activity, and the potential for post-RP1 lithospheric strengthening beneath the Stord Basin (Naliboff & Buiter, 2015), we suggest that upwelling asthenosphere associated with RP2 would be channeled beneath the South Viking Graben and buttressed by the Utsira High and Lomre Shear Zone to the east, resulting in the Stord Basin and Northern Horda Platform remaining inactive during RP2 (Figure 14).

9.4. Fault Interactions During Multiphase Rifting

Based on the geometry and distribution of syn-rift depocenters, we observe that the N-S striking faults across the Northern Horda Platform were active in RP1, inactive during RP2, and later reactivated during Late-syn- to Post-RP2 (Figures 6, 11, and 13). This RP2 inactivity and Late-syn- to Post-RP2 reactivation contrasts with observations across East Shetland Platform, where fault activity is recorded during RP2 before reducing in Late-syn- to Post-RP2. This reactivation of faults across the Northern Horda Platform is associated with the formation of NW-SE striking faults between the main N-S striking faults, although these are not resolved in this study (Duffy et al., 2015; Whipp et al., 2014). These NW-SE striking faults do not match with the proposed E-W to NW-SW oriented extension directions proposed for RP2 and are instead proposed to be related to local stress perturbations surrounding the larger N-S striking faults (Duffy et al., 2015; Reeve et al., 2015; Whipp et al., 2014), showcasing a similar mechanism to that observed between the shear zones and rift-related faults during RP1 (Figure 15).

In the East Shetland Basin, optimally aligned (i.e., N-S striking) RP1 faults were often not reactivated during RP2 (Claringbould et al., 2017; Tomasso et al., 2008). RP2 extension across the East Shetland Platform was largely accommodated by the formation of new, mostly east dipping faults that crosscut the preexisting structures (Figure 9). Claringbould et al. (2017) propose that the lack of reactivation may reflect the increasing influence of thermal effects arising from previously thinned lithosphere, with the rift narrowing process causing incipient faults to preferentially dip toward the rift axis (Claringbould et al., 2017; Cowie et al., 2005). A similar process occurs in the East African rift; strain is initially accommodated over a wide area under the influence of preexisting structures, before becoming localized toward the rift axis and neglecting the presence of any preexisting structures (Corti, 2009; Ragon et al., 2018).

10. Conclusions

In this study we document the regional-scale evolution of the North Sea throughout late Permian-Early Triassic and Late Jurassic-Early Cretaceous phases of extension. We evaluate how syn-rift depocenters and their associated normal faults evolve throughout multiple phases of rifting and assess the impact of structural inheritance.

Through documenting the regional-scale multiphase evolution of the northern North Sea rift, and comparing it to the detailed catalog of preexisting structural heterogeneities beneath the rift, we show that

1. Rift geometry and activity was highly spatially and temporally variable across the northern North Sea during late Permian-Early Triassic (RP1) and Late Jurassic-Early Cretaceous (RP2) rift events.
2. Extension occurred over an ~200-km-wide area during RP1, from the East Shetland Basin to the Northern Horda Platform in the north and from the South Viking Graben to the Stord Basin in the south. The location of major depocenters during RP1 appears to have been heavily influenced by the presence of Devonian basement shear zones, the Utsira Shear zone and Øygarden/Hardangerfjord Shear zones align with the bounding faults of the Stord Basin, while faults in the East Shetland Basin mirror the geometry and dip direction of the underlying Tampen, Brent, and Ninian shear zones.

3. Strain is transferred from the Stord Basin/Northern Horda Platform along the eastern margin of the rift in the south, to the East Shetland Basin along the western rift margin further north. The site of this strain transfer corresponds to the Lomre Shear Zone.
4. Rift-related faults may reactivate or align along preexisting structures such as the Devonian shear zones either due to the reactivation of internal anisotropies or due to local stress perturbations around the structure. In addition, shear zones situated at high angles to the regional stress field may be responsible for the segmentation of individual faults and rift basins, including the Viking Graben.
5. Rift activity localizes onto the Viking and Sogn grabens during RP2, with negligible reactivation of structures along the eastern rift margin, that is, the Stord Basin and Northern Horda Platform. The eastern margin of activity during RP2 is delineated by the Utsira High in the south and the Lomre Shear zone further north.
6. As extension in the northern North Sea wanes during the latter stages of RP2, rift activity migrates northward toward the Sogn Graben and the Marulk and Magnus Basins. This migration of rift activity reflects extension related to the opening of the North Atlantic Ocean becoming the dominant regional stress. Increased rift activity in the north of the study area drives the local flexural reactivation of faults across the Northern Horda Platform.
7. The Utsira High represents a long-lived structural high that resists extension throughout RP1 and RP2. Following RP1, we propose that increased lithospheric thickness was preserved beneath the Utsira High with thinned lithosphere beneath the Stord Basin and South Viking Graben. As a result, we suggest that activity during RP2 was focused beneath the South Viking Graben and pinned eastward at the Utsira High and Lomre Shear zone, causing the Stord Basin and Northern Horda Platform to the east to largely remain inactive.
8. The influence of preexisting structural heterogeneities, here represented primarily by Devonian shear zones, exert a diminished influence over rift physiography during later rift phases. Although they delineate the boundary to activity during RP2, they do not control the main depocenters. The Viking Graben instead appears to be more influenced by modification of the lithospheric structure associated with the earlier phase of rifting.

We highlight how structural inheritance and multiple phases of rifting influence the regional geometry and evolution of rift systems. Preexisting structural heterogeneities that are relatively well aligned with the rift dictate the initial geometry of major rift-related faults and their associated syn-rift depocenters, while those oriented at relatively high angles to the rift may segment faults and rifts. Furthermore, we show how rift activity migrates and localizes across the rift during multiple phases of rifting, showing a decreased influence from structural inheritance and an increased role from thermal effects associated with prior phases of lithospheric thinning. However, preexisting structures still exert some control over rift physiography and kinematics during these later events, determining the areas of rift activity and whether certain faults will be reactivated.

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