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Structural Observations of the Northern North Sea: Insights into Rift Failure Dynamics

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Abstract Lithospheric extension leads to rift formation and may continue to the point of breakup, with oceanic ridge initiation and the formation of two conjugate rifted margins. In some settings, extension can cease, and the rift may be abandoned. These so-called failed rifts archive snapshots of early phases of deformation, with geometries that may help better constrain the parameters that can prevent a rift from reaching breakup, such as lithospheric rheology, thermal state, rift opening direction and rate, inheritance. This contribution summarizes a study of the Norwegian Continental Shelf which includes the North Sea Rift and the Møre and Vøring rifted margins. We proceeded to the interpretation of a new dataset of deep penetrating seismic reflection profiles and worked at the regional scale, deliberately ignoring local particularities, to focus on the large-scale structural picture. The aim is to list architectural similarities and differences between the failed rift and the successful rifted margins. Our mapping shows that the North Sea structural geometries and basement seismic facies are very similar to the observations listed for the adjacent Møre and Vøring rifted mar-gins. Various types of tectonic structures are observed, from thick anastomosing shear zones possibly evolving into core-complex geometries, to composite large-scale detachment faults and standard high-angle normal faults. These are categorized into five classes and interpreted as exemplifying the rift tectonic evolution through distinct generations of deformation structures that can activate, de-activate and re-activate. Based on these observations, rift failure dynamics are discussed, and it is proposed that the North Sea rift abandonment may not be related to pre-rift local conditions but rather to the ability to initiate specific tectonic structures such distal breakaway complexes.

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1 Introduction

Continental rifts are formed under extensional tectonics and may ultimately lead to the formation of conjugate rifted margins after lithospheric breakup. However, in some set-tings, extension does not persist to the point of breakup and the rift is abandoned. These failed rifts are interesting as they archive early stages of extensional deformation which are often not accessible any longer in rifted margins, where the subsequent phases of deformation have overprinted the initial geometries. Such abandoned rifts are relatively common and can be found in both onshore and offshore settings, such as in North America with the Midcontinent Rift *Stein et al.* (2018), in the North Atlantic Ocean with the Orphan Basin (*Welford et al.*, 2019, 2012), Porcupine Basin (*O'Reilly et al.*, 2006; *Lymer et al.*, 2023), Rockall Trough (*Klingelhöfer et al.*, 2005; *MacMahon et al.*, 2020), or in the South China Sea (e.g., the Baiyun Sag; *Wang et al.*, 2018), the East Natuna Basin (*Savva et al.*, 2014) or the Xisha Trough (*Lei and Ren*, 2016).

Rifts may be abandoned for various reasons. Determinant factors are the mechanical strength of the crust, an insufficient magma supply, a modification in regional tectonic forces, the coexistence of several rift arms or a too elevated thermal state (e.g., *Huismans and Beaumont*, 2007; *Brune et al.*, 2017, 2014; *Glerum et al.*, 2020; *Heine et al.*, 2013; *Nirrengarten et al.*, 2020; *Li et al.*, 2020). From the structural point of view, even though the rift fails, the basement thinning can be severe with crustal thicknesses possibly reduced down to few kilometres, and mantle exhumation (e.g., Phu Khan Basin; *Savva et al.*, 2014). Thus, the structural geometries can be issued from a wide range of deformation modes from stretching to hyperextension and exhumation.

This contribution summarizes a study focused on the North Sea rift. The purpose is to take advantage of a new long-offset deep penetrating dataset which covers the entire Norwegian offshore extensional system including the failed rift of the North Sea and the two adjacent Møre and Vøring rifted margins (Figure 1). As the dataset covers both systems with profiles characterized by same acquisition and processing parameters, it allows an interesting

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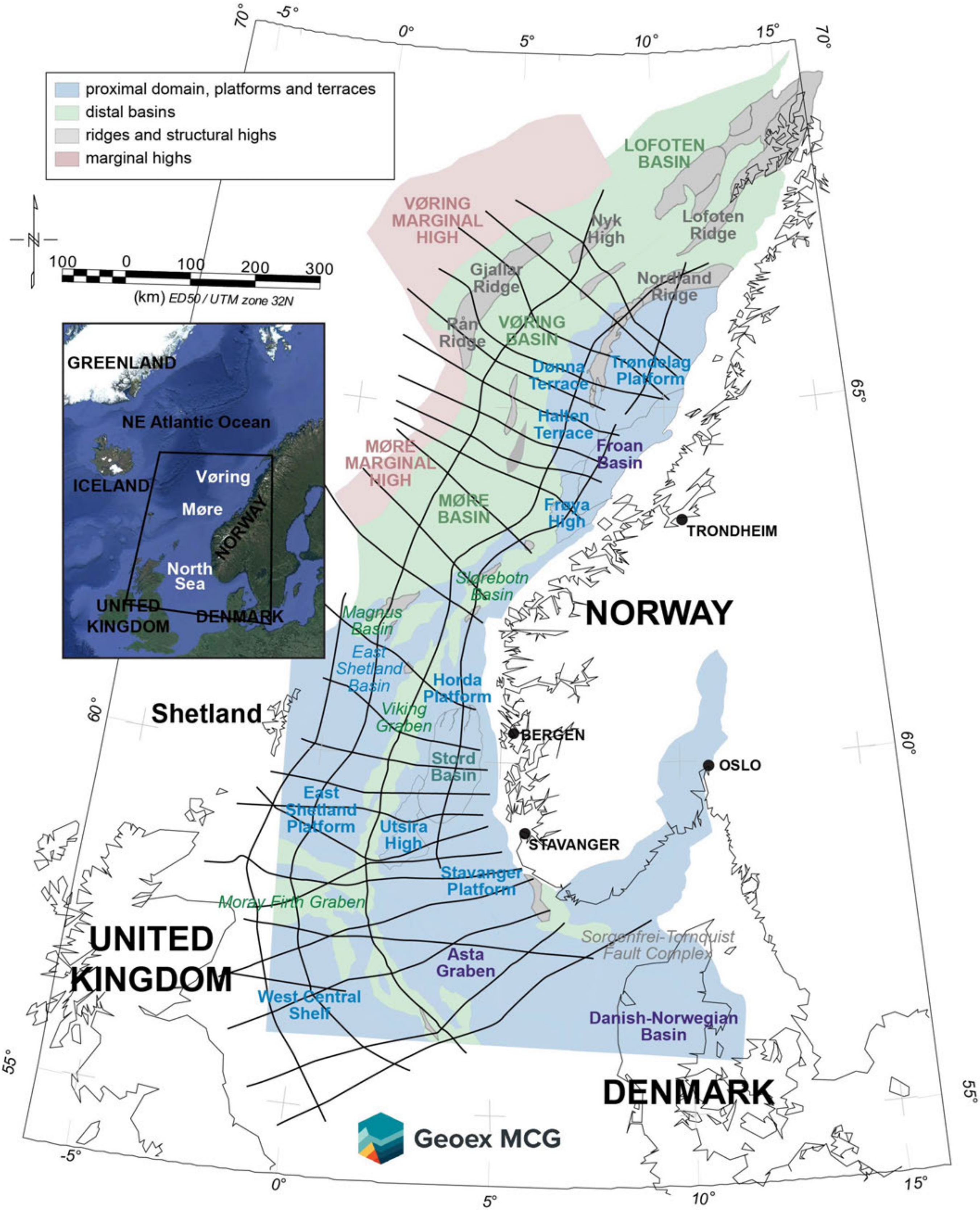


Figure 1 – Structural map of the Norwegian Continental Shelf, from the Denmark to the Norwegian Lofoten archipelago, including the North Sea Rift and the Møre and Vøring rifted margins. The offshore coloured polygons are from the NPD structural map (*Brekke*, 2000; *Blystad*, 1995). In blue and violet: proximal domain, platforms and terraces. In green: distal and rift basins. In grey: ridges and structural highs. In red: magmatic margin-al highs. The thin black lines represent the dataset used in the study (Geoex MCG RDI18-19-21). The inset on the left shows where the study region stands within the North-East Atlantic Ocean.

comparison exercise. Based on the analysis of the seismic facies and basement structures, the aim is to map – at regional scale – the main tectonic geometries that are responsible for today's observed architecture. The structural differences and similarities between the rifted margins and the abandoned rift are listed and used in a discussion spanning the various scenarios that may explain the rift failing. Focus is set on the structural geometries to add pages to our catalogue of observations.

2 Geological Setting

The North Sea rift lies offshore in between North-East United Kingdom, South-West Nor-way and Denmark (Figures 1 and 2). Driven by the hydrocarbon reserves studies, the area has been extensively studied for the last four decades.

The North Sea area is famous for its multiphase rift evolution and considered as an exceptional laboratory to study the influence of structural inheritance on subsequent tectonic activity (e.g., *Bartholomew et al.*, 1993; *Bell et al.*, 2014; *Duffy et al.*, 2015; *Fossen et al.*, 2017; *Phillips et al.*, 2016; *Fazlikhani et al.*, 2017; *Lenhart et al.*, 2019). The structures ob-served today correspond to Late Paleozoic - Mesozoic extensional events that settled on terranes which previously went through other major geological events, with the Variscan and the Caledonian orogenies and the subsequent excision of their over-thickened crust. Structurally, the North Sea rift corresponds to a series of linked elongated basins and structural highs (e.g., *Ziegler*, 1989; *Bartholomew et al.*, 1993; *Færseth*, 1996) (Figures 1 and 2). In the study area, focused on the northern part of the rift, these basins are roughly oriented North-South, and rifting is traditionally summarized in two main rift phases (e.g., *Faleide et al.*, 2015; *Evans et al.*, 2003) with 1. A Late Permian - Early Trias rift axis ('Rift Phase 1'; Bell et al., 2014); and 2. A Mid-Late Jurassic - Early Cretaceous rift axis centred beneath the today's Viking Graben ('Rift Phase 2'; *Bell et al.*, 2014). Each rift phase was followed by a period of thermal cooling subsidence.

3 Dataset

The seismic reflection profiles used in this study are from the Regional Deep Imaging (RDI) 18 and 21 dataset from Geoex MCG. These are long-offset, deep penetrating, 16-stwtt profiles which image the entire extensional system, from the seafloor to the upper mantle including the lower basement and Moho. This dataset is unique in the Norwegian Conti-nental Shelf as it allows for the first time a regional evaluation of the basement seismic facies, geometries and thinning over the whole extensional system. For the discussion purpose, a previous study of the RDI19 Geoex MCG dataset which covers the Møre and Vøring rifted margins is integrated (*Peron-Pinvidic et al.*, 2022). Figures 3, 4 and 5 show a selection of profiles with and without interpretation that are summarized and discussed below.

Practically, we complemented the seismic interpretation with analysis of the dense net-work of the NSR (North Sea Renaissance) and MNR (Mid Norway Renaissance) seismic re-flection profiles and older datasets available from the DISKOS database, which cover the entire Norwegian Continental Shelf including the North Sea and the Møre and Vøring rifted margins.

4 Observations and First Order Interpretations

The purpose of this contribution is to discuss the deformation tectonic structures at rift scale. Therefore, the mapping aimed at catching the large-scale picture and deliberately avoided details of local features. Comprehensive high-quality investigations done on high-er resolution dataset have been shown notably by *Lenhart et al.* (2019), *Fazlikhani et al.* (2017), and *Phillips et al.* (2016). Here, we mapped a series of key horizons – termed core envelopes - that help constrain the tectonic history of the study region: the seafloor, top-acoustic basement, and Moho. These surfaces permit to evaluate the amount of basement thinning and subsidence and thus assess the main tectonic history of the region. In addition, two basement units have been defined based on their seismic facies, together with a series of deformation structures. The main observations are summarized below, before being discussed in the next section, focusing on the rift failure question.

4.1 The Basement

For studying the structural geometries of the area, an acoustic top-basement horizon is defined. The resulting core envelope corresponds to the surface on top of which the Permo-Trias Rift Phase 1 settled (Figures 3-5). The rocks above the top-acoustic basement show typical sedimentary geometries with a well layered pattern with conformable sub-parallel reflectors of medium amplitude. These sediments drape and onlap the below topography and often form wedges with reflectors diverging towards the fault planes in the sub-basins (e.g., pointing arrows inn the Stord Basin in Figure 3, and Magnus Basin in Figure 5).

The unit below the top-basement envelope shows medium to low reflectivity, with a relatively more transparent to chaotic seismic facies (e.g., arrows pointing both the sediments and basement in the Stord Basin in Figure 3). The rocks can correspond to pre-rift crystalline rocks, but can also encompass various other lithologies, such as those related to the orogen and orogenic collapse (e.g., Devono-Carboniferous sedimentary basins) (*Bartholomew et al.*, 1993; *Fossen et al.*, 2014; *Fazlikhani et al.*, 2017; *Lenhart et al.*, 2019).

Deeper, the lower basement unit is well-defined with a distinct high reflectivity (Figures 3-5, with

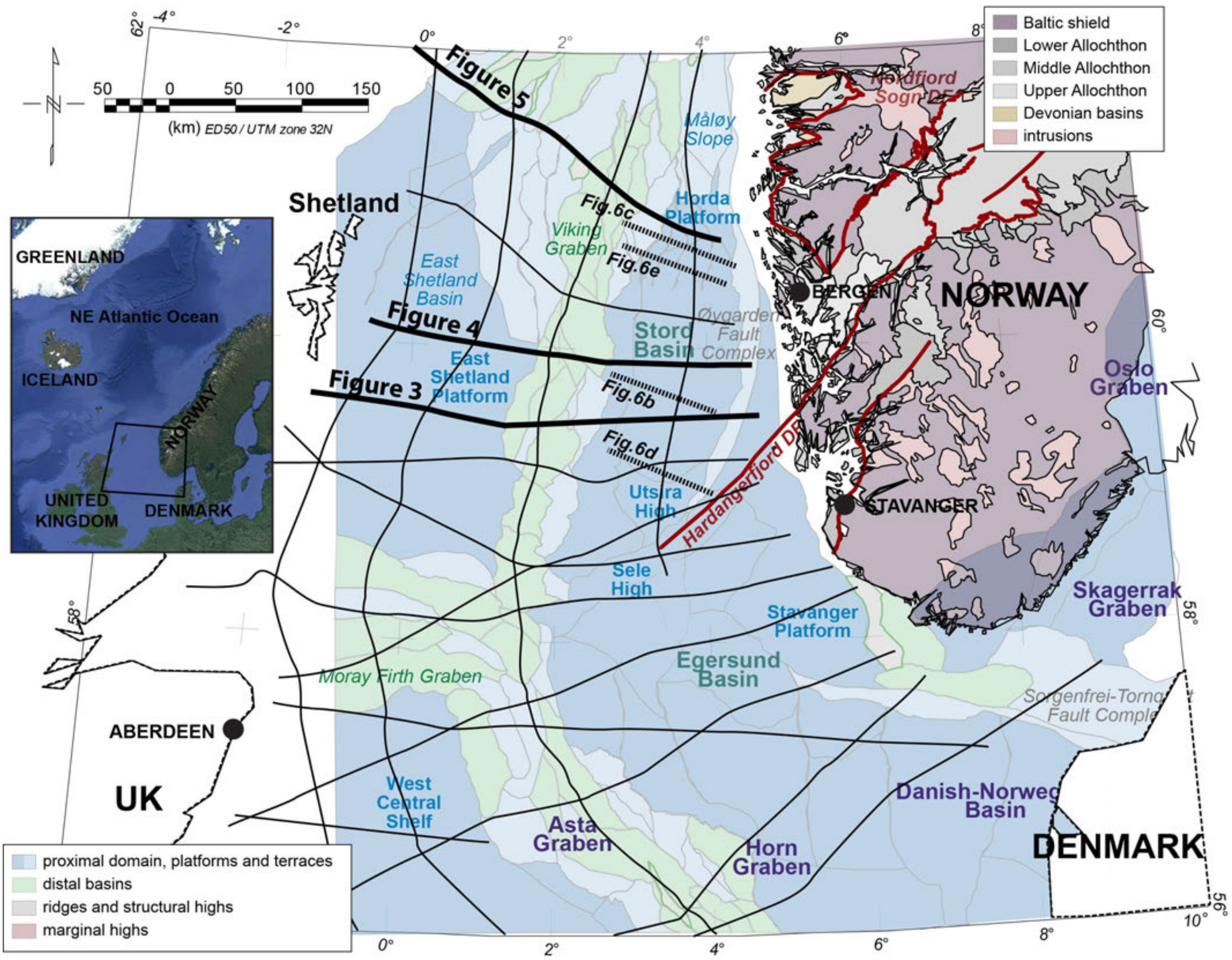


Figure 2 – Structural map of the North Sea Rift, with location of this contribution's Figures 3 to 6.

pointing arrows). It is typified by a series of packages of medium to high amplitude reflectors which are subcontinuous and undulating. This reflective lower crust has early been identified and mapped as 'transitional zone between an overlying transparent middle and upper crust and the underlying mantle' (*Christiansson et al.*, 2000). It is usually in-terpreted as an assemblage of basement of Proterozoic and Paleozoic Caledonian origin, organized in an overall regional boudinage fabric (e.g., *Fossen et al.*, 2014; *Fazlikhani et al.*, 2017; *Lenhart et al.*, 2019).

The Moho is mapped as the bottom envelope of the lower basement reflective unit. This unit corresponds to all medium to high amplitude reflectors and diffuse reflectivity ob-served at lower basement depths (Figures 3-5). Depending on the location, it can correspond to a diffuse downward decrease in the reflectivity of the lower basement unit or to well defined high amplitude reflectors (e.g., pointing arrow to sharp Moho on Figure 4). The Moho usually corresponds to the base of the continental crust – top of the upper mantle. However, in some settings, the seismic reflection Moho is mapped at depths exceeding 12s TWTT (e.g., question mark in Figure 3, under the Utsira high), what would correspond to depths probably exceeding 35-40 km. Although thick crust is not excluded, alter-native basement compositions may also be considered such as mafic intrusions and/or underplatings, altered (deformed, intruded) mantle and metaperidotites (*Fichler et al.*, 2011).

The basement below the Moho envelope is characterized by a much lower reflective facies and lower amplitude reflectors than the above basement units. When observed, the reflectors are rather isolated, often disorganized in short events with no identifiable specific pattern (Figures 3-5). Some high-amplitude events are however observed at various locations (Figures 3-5). *Christiansson et al.* (2000) interpreted these as intra-mantle faulting.

4.2 The Tectonic Structures TS

Different categories of faults have been mapped, including normal faults, detachment faults and mylonitic shear zones. Below, we divide them into five classes that we interpret as representative of the main tectonic deformation modes that the area went through since extensional deformation began with

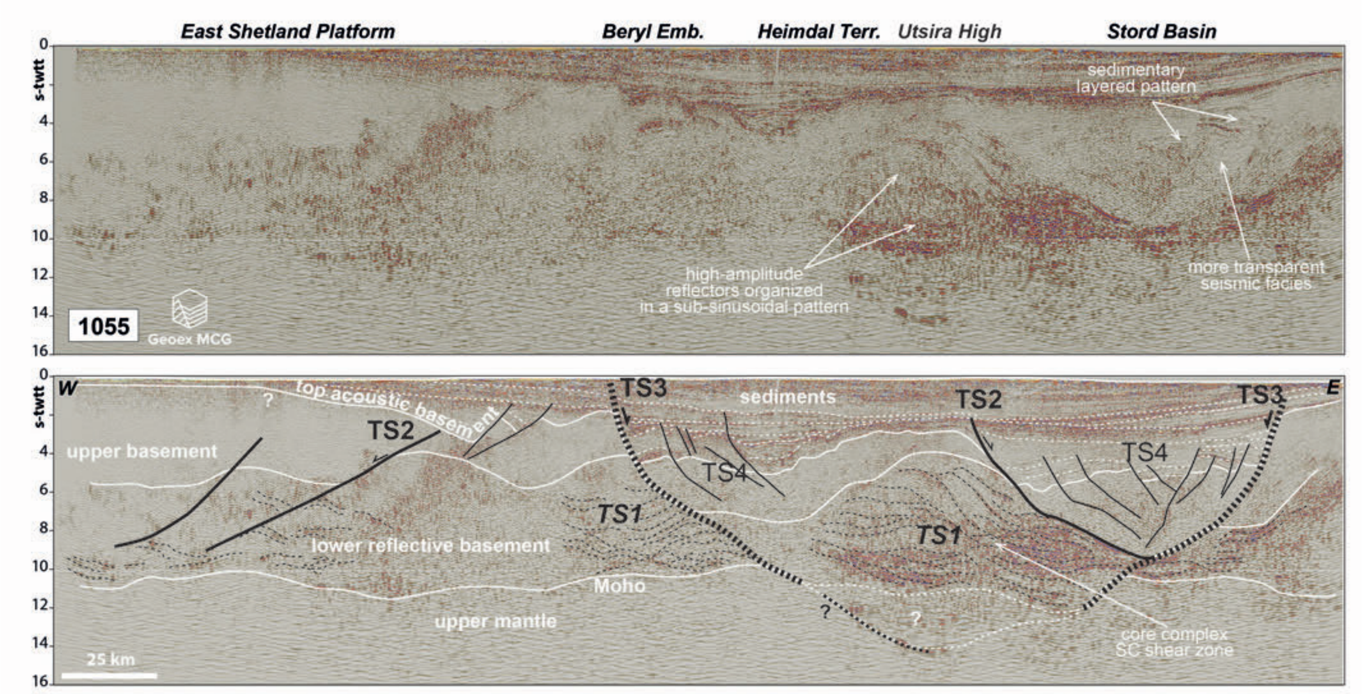


Figure 3 – Seismic reflection profile illustrating the structural setting of the North Sea rift (courtesy of Geoex MCG). Top: without interpretation. Bottom: interpreted version. See text for expla-nations and Figure 2 for location. TS: Tectonic Structure.

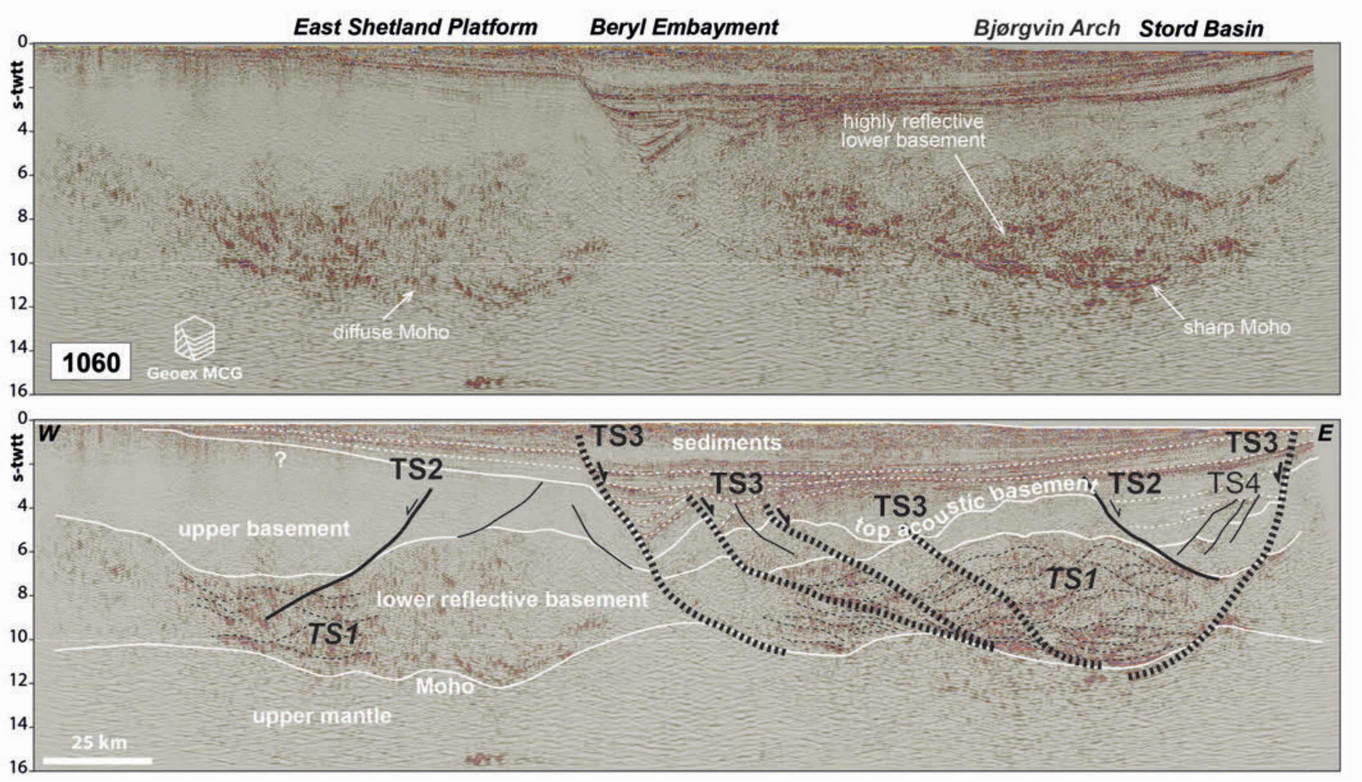


Figure 4 – Seismic reflection profile illustrating the structural setting of the North Sea rift (courtesy of Geoex MCG). Top: without interpretation. Bottom: interpreted version. See text for expla-nations and Figure 2 for location. TS: Tectonic Structure.

the orogenic collapse. These are labelled TS 1 to 5, with TS standing for Tectonic Structure. Figures 3-5 show images of the key regional seismic profiles, with and without interpretation to illustrate the mapping strategy. Figure 6 proposes seismic extracts from another dataset (NSR North Sea Renaissance, Diskos database) to illustrate the robustness of the TS identification on all seismic data sets.

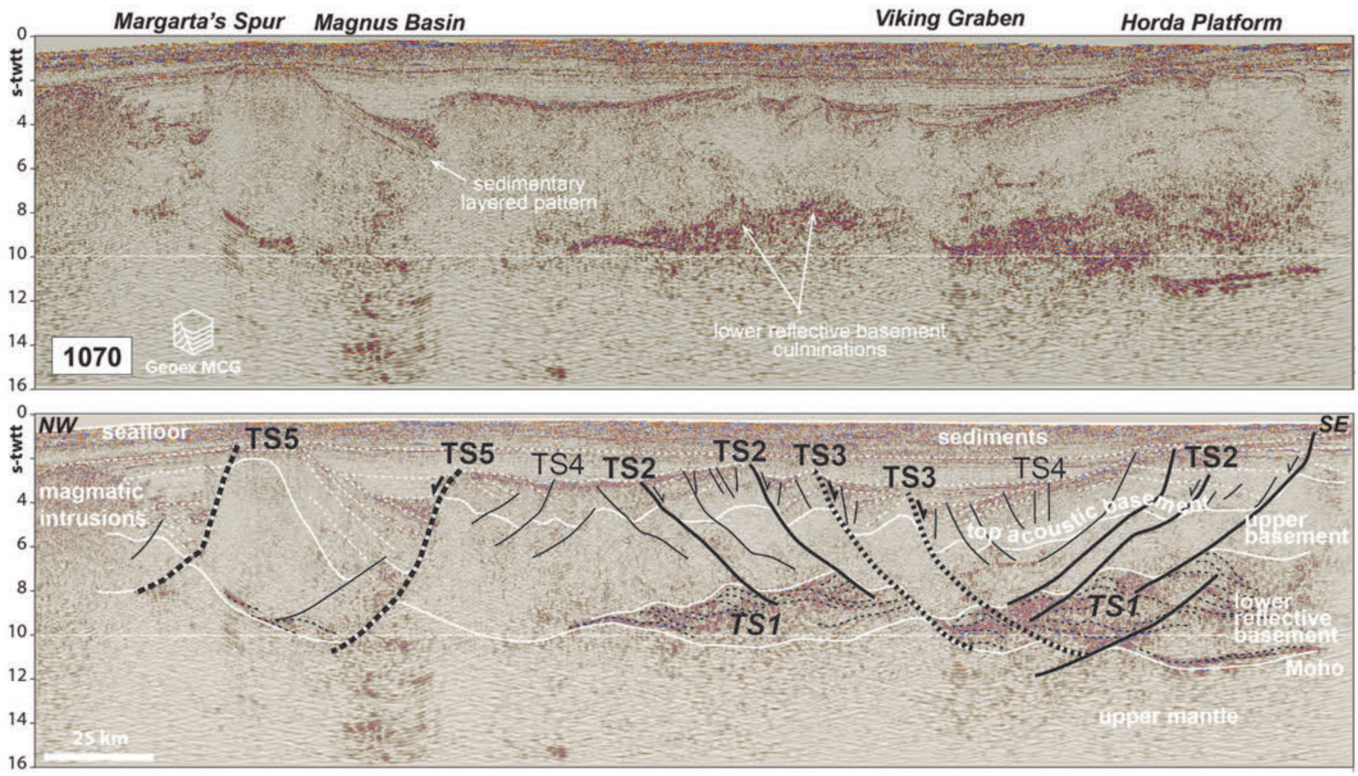


Figure 5 – Seismic reflection profile illustrating the structural setting of the northern part of the North Sea rift to the distal Møre rifted margin (courtesy of Geoex MCG). Top: without interpreta-tion. Bottom: interpreted version. See text for explanations and Figure 2 for location. TS: Tectonic Structure.

4.2.1 TS1: Anastomosing Shear Zones & Core Complexes

Tectonic Structure 1 (TS1) corresponds to packages of high amplitude reflectors observed within the lower reflective basement (Figures 3-5). These multi-layers thick units often dis-play undulating conformable medium to high amplitude reflectors. These are organized into a specific sigmoidal fabric with convergence and divergence of sub-continuous reflec-tors in 'SC' like – anastomosing patterns (Figures 3-5, pointing arrow in Figure 3, Utsira High on Figure 6b.). TS1 is interpreted to correspond to anastomosing shear zones which attest to intensive localized ductile deformation in between pieces of more competent basement. These shear zones which can develop at some locations into spectacular core complex-like structures (e.g. Utsira High on Figures 3 and 4), and have been interpreted as major ductile deformation inherited from the orogenic collapse (e.g., *Fazlikhani et al.*, 2017; *Serck et al.*, 2022).

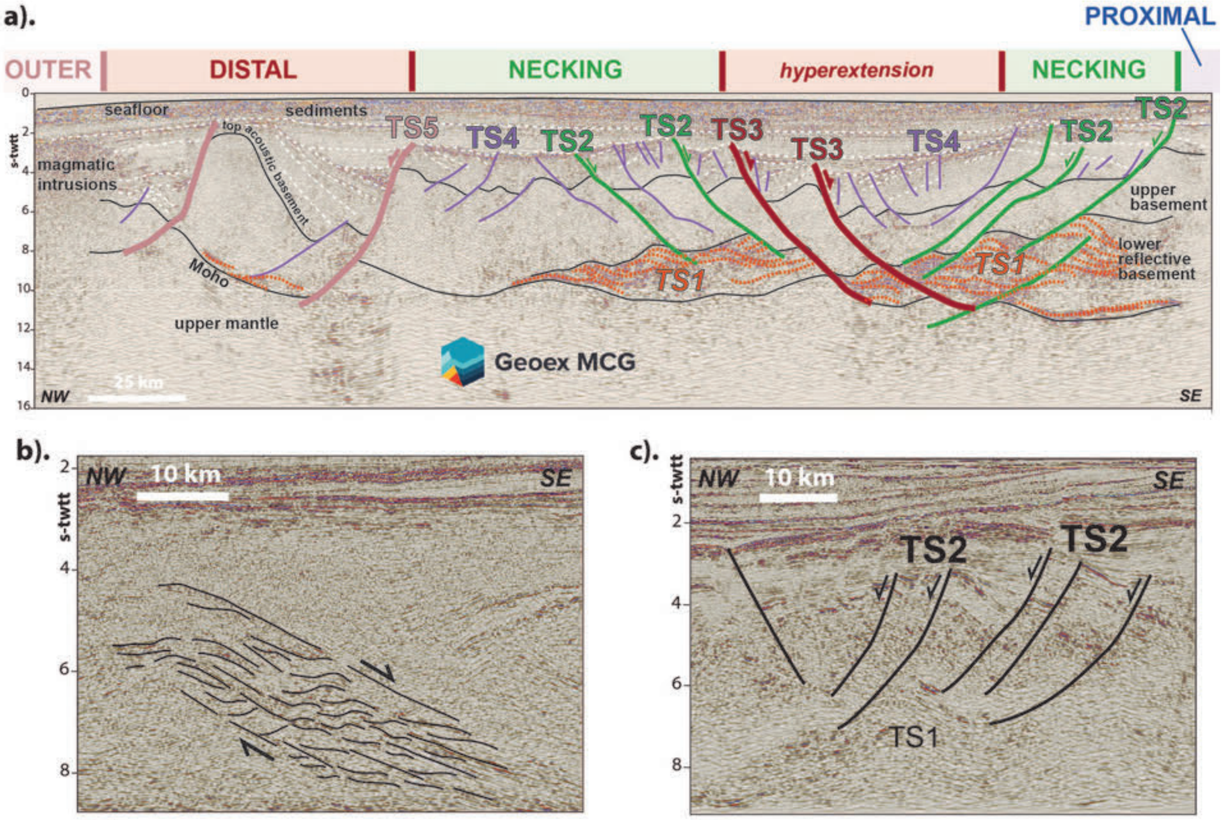
Some of the higher amplitude reflectors or group of reflectors within TS1 could represent mafic intrusions, as seismic facies show sometimes abrupt impedance contrast. However, the widespread distribution, the often internal 'SC' pattern geometries, and the direct onshore correlation to mapped outcrops of shear zones (e.g., the Hardangerfjord, Karmøy, Stavanger shear zones) favour the shear zone interpretation, as suggested by many authors (e.g., *Fossen et al.*, 2014; *Gabrielsen et al.*, 2015; *Fazlikhani et al.*, 2017; *Serck et al.*, 2022). Some intrusions are however not to be excluded for local occurrences (*Wrona et al.*, 2019).

4.2.2 TS2: Detachment Faults

Tectonic Structures 2 (TS2) encompass a network of large-scale detachment-type faults (Figures 3-5). These well-defined structures present sub-regional extents and accommodate significant displacements (Figures 3-5). They affect both sedimentary and basement units flanking half-graben sedimentary basins, cutting upper basement, and rooting on TS1 culminations (e.g., Figure 5 and Horda Platform in Figure 6c). The geometries are often segmented, suggesting a probable multiphase activity. Syn-tectonic structural interaction with the TS1 shear zones culminations is observed at most locations (see dragging deflecting TS1 reflectors in the vicinity of TS2 faults, Figures 3-5). However, TS2 faults never cut through the entire basement. They root deepest at lower-basement levels and TS1 culminations implying decoupled deformation at basement scale. The overall geometries and interaction with more ductile levels in the basement are similar to the inner necking breakaway structures defined in the Møre and Vøring rifted margins (*Osmundsen and Péron-Pinvidic*, 2018).

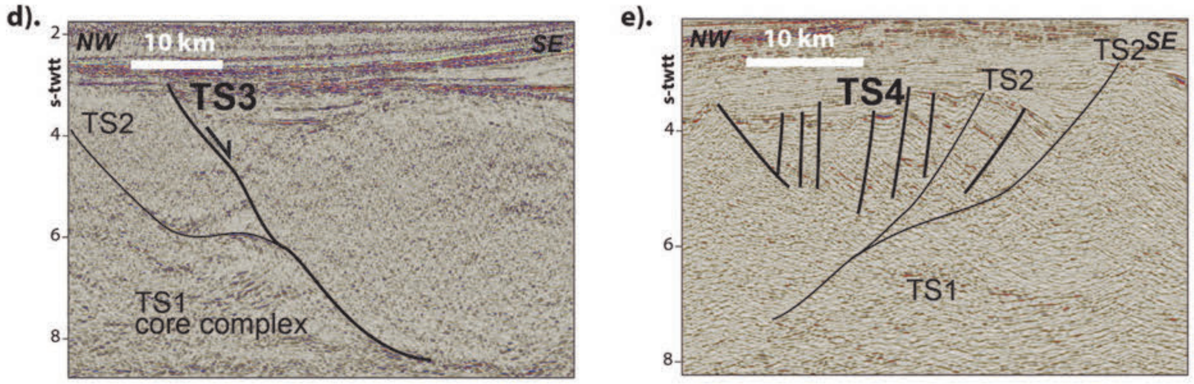
4.2.3 TS3: Large-Scale Detachment Faults

Tectonic Structures 3 (TS3) are very similar to that of TS2 and interpreted as further de-veloped versions of these. However, TS3 show slightly more complex



TS1
well-defined thick unit at lower-basement depths, with distinct high-reflectivity seismic facies and frequent sinusoidal shear pattern
= thick shear zones, possibly developing in core complexes geometries (e.g., Utsira High)

TS2
well-defined planar structures flanking half-graben-types sedimentary basins, cutting upper basement and rooting on TS1 culminations
= brittle normal faults
--> inner necking breakaway complex



TS3
large-scale undulating segmented structures, cutting through the whole crust, including TS1, with possible strong structural relationship with TS1
= brittle-ductile detachment faults
--> outer necking breakaway complex

TS4
well-defined small-scale planar structures, cutting through sedimentary sequences and upper basement
= brittle normal faults

TS5 - not observed in the North Sea - observed in the rifted margin context of Møre & Vøring
well-defined planar to upward-concave structures
cutting through the embrittled crust without structural relationship with TS1
= detachment faults / distal domain breakaway complex

Figure 6 – a) After Figure 5. Seismic reflection profile illustrating the structural setting of the north-ern part of the North Sea rift to the distal Møre rifted margin (courtesy of Geoex MCG). The main faults are mapped and labelled based on the various defined tectonic structures (TS). **b)** Seismic extract from another dataset (NSR, North Sea Renaissance) illustrating the TS1 typical anastomosing shear-zone geometries. **c)** Seismic extract (NSR) illustrating the TS2 well-defined planar to slightly upward concave geometry. **d)** Seismic extract (NSR) illustrating the TS3 large-scale undulating pattern and interaction with TS1 culminations. **e)** Seismic extract (NSR) illustrating the TS4 local extent and high-angle typical geometry. TS5-type of faults can be observed on the a) seismic profile within the Møre distal margin but are not observed within the North Sea. See Figure 2 for location.

and extended geometries cutting through the whole basement, including TS1, from the top-basement to the Moho and upper mantle (Figures 3-6). The overall architecture tends to adapt to pre-existing fabrics, displaying large-scale undulating segmented fault planes with dips varying from high to low angles, including upward and downward concave segments. These geometries suggest a deformation mode that is coupled through the entire basement, with probable composite tectonic deformation including brittle and ductile/semi-ductile behaviour. The fact that TS3 faults dissect the lower basement unit without systematic tectonic interaction with TS1 suggests that the TS1 shear zones are probably mostly deactivated and partly embrittled at time TS3 are active. Thus, these TS3 structures mark a significant change in the tectonic deformation of the rift. TS3 faults are interpreted to deeply structure the rift, flanking areas of thinned crust and deeper sedimentary basins, and are interpreted to be equivalent to the outer necking breakaway complexes defined on the Møre and Vøring rifted margins (*Osmundsen and Péron-Pinvidic*, 2018; *Gresseth et al.*, 2023).

4.2.4 TS4: High-Angle Brittle Normal Faults

Tectonic Structures 4 (TS4) correspond to high angle normal brittle faults crosscutting the pre-existing fabric without major structural relationship with the other tectonic structures. TS4 are sub-planar, straight to slightly upward concave fault planes (Figures 3-6). They cut the upper basement unit into tilted blocks and flank half grabens characterized by tilted sedimentary layers (e.g., Stord Basin area in Figure 3, Horda Platform in Figure 6e.). TS4 faults have only a local extent and are associated with low beta factors of extension.

4.2.5 TS5: Detachment Faults

Tectonic Structures 5 (TS5) are not identified in the North Sea rift. These are observed within the rifted margin context of the adjacent Møre and Vøring margins. They are well-defined sub-planar to upward-concave structures cutting through the embrittled basement without structural relationship with the other tectonic structures (Figures5 and 6a.). TS5 are interpreted as detachment faults, equivalent to the distal and outer breakaway complexes defined by *Osmundsen and Péron-Pinvidic* (2018). They accommodate the final excision of the embrittled basement within the distal domain of the Møre and Vøring rifted margins.

4.3 Regional Implication

Decades of research on the Norwegian Continental Shelf have led to the identification and characterisation of a long list of tectonic structures (e.g., *Blystad*, 1995; *Tsikalas et al.*, 2012). Based on a regional approach, *Osmundsen and Péron-Pinvidic* (2018) proposed to categorize the main bordering faults as specific breakaway complexes that delineate the margin's structural domains - the so-called proximal, inner necking, outer necking, distal and outer breakaway complexes. These can be used as markers to map the structural domains characteristic of the margin (*Peron-Pinvidic et al.*, 2013). Figure 7 proposes such a map based on the observations and results listed in this contribution. For instance, the TS2 detachment faults are interpreted as characteristic of the necking domain, where the crust is thinned but not yet fully embrittled. TS3 large scale detachment faults are associated to the distal domain where the crust is thinned down under a certain threshold and totally embrittled allowing the detachment faults to cut through the entire basement and reach the upper mantle. TS5 structures are interpreted as equivalent to the distal and outer breakaway complexes and thus associated to the outer structural domain which is observed exclusively in the rifted margin context (Figure 7). In addition to the Figure 7 map, Figure 8 depicts a selection of six seismic profiles issued from the same GeoexMCG dataset, from the northern Vøring margin to the North Sea rift. The three profiles at top (A, B, C) are issued from a previous publication (*Peron-Pinvidic et al.*, 2022) and the three at the bottom (C, D, E) correspond to the Figures 3, 4 and 5 of this contribution, respectively. These profiles all display comparable facies and geometries, including the range of TS tectonic structures and bipartition of the basement into two distinct units, what tend to underline the strong architectural similarities between the rift and the rifted margins.

5 Discussion

Various parameters, and/or combination of parameters, can influence the failure of a rift to reach breakup, such as lithospheric rheology, thermal state, rift opening direction and rate, inheritance. Thus, it may be difficult to constrain all possible scenarios. Factors related to the basement rheology, magma supply, or the lithospheric thermal state are not in-vestigated in this study. Here we limit our discussion to the structural interpretation of the geometrical observations which are possible based on our dataset. The exercise consists in trying to find what differentiates the North Sea rift geometries from the Mid Norwegian rifted margins.

5.1 Rift Failure Scenario 1: the Basement Responsibility?

The North Sea basement has been extensively studied and various contributions proved its complexity providing high-quality mapping of the different basement types that can be considered (e.g.. *Phillips et al.*, 2016; *Fazlikhani et al.*, 2017; *Lenhart et al.*, 2019; *Phillips et al.*, 2019; *Serck et al.*, 2022). We here worked on a rift-scale picture and only defined two basement units (see above Section 4.1). Our mapping shows that the basement displays similar

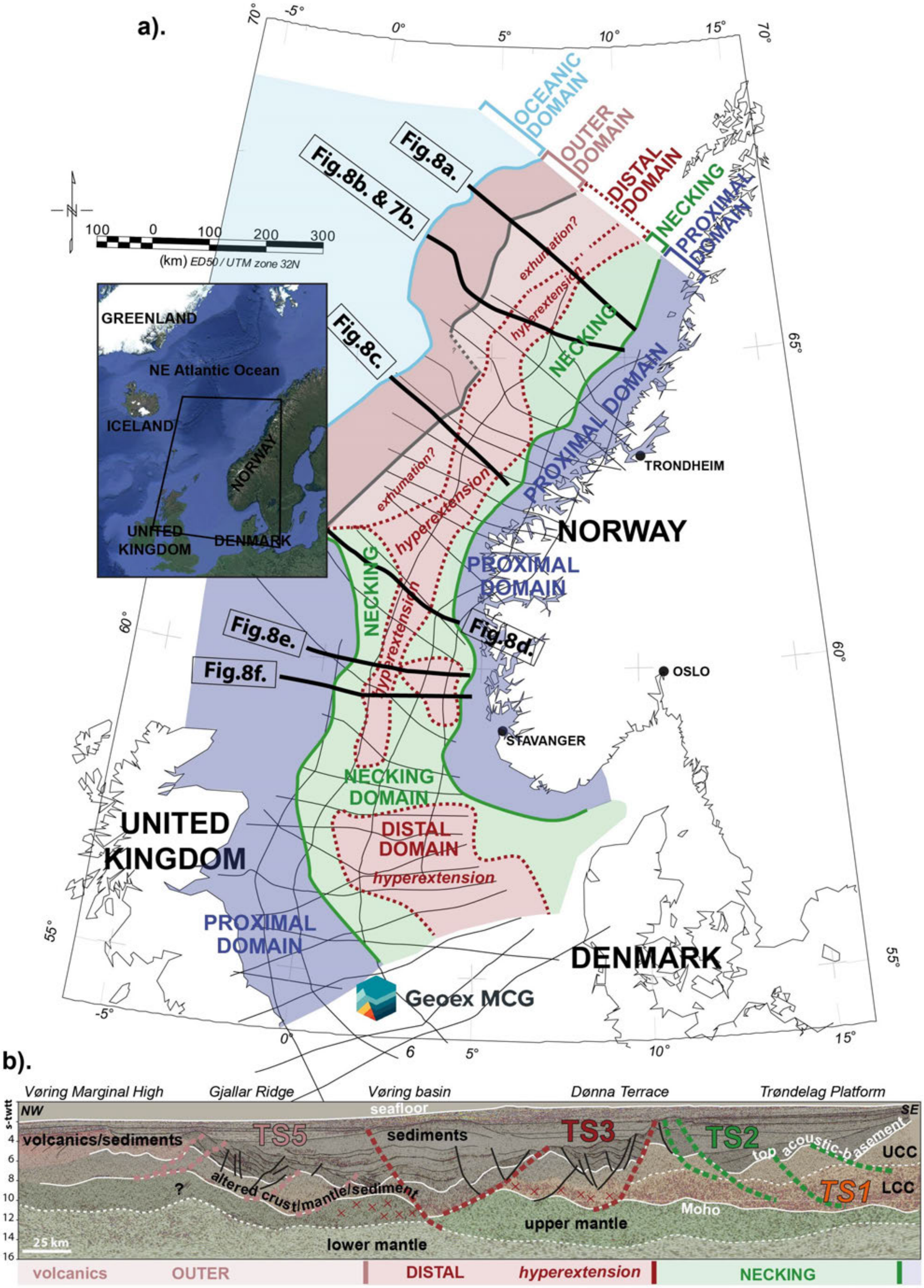


Figure 7 – **a)** Map of the structural domains (proximal, necking, distal, outer, oceanic) over the Norwegian Continental Shelf, with location of the seismic profiles proposed as type examples in Figure 8. **b)** Seismic reflection profile selected as representative of the architecture of the Mid-Norwegian margin. Modified after *Peron-Pinvidic et al.* (2022).

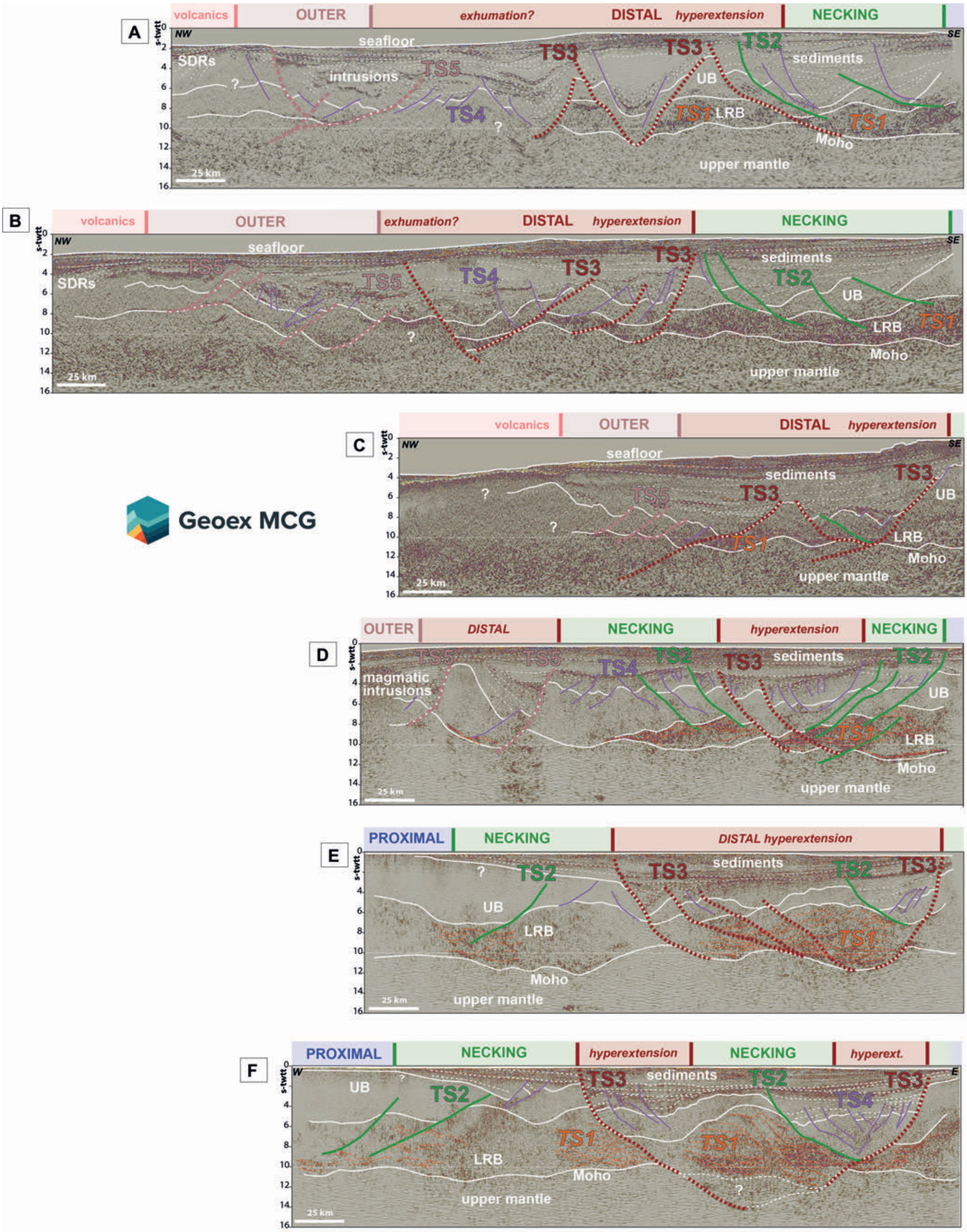


Figure 8 – Selection of 6 type-example seismic reflection profiles over the Norwegian Continental Shelf (courtesy of Geoex MCG). Profiles A, B and C are modified from *Peron-Pinvidic et al.* (2022). Location on Figure 7. These profiles show the identification of the various tectonic structures (TS) and the related structural domains. Note that, although the North Sea rift shows structures characteristic of the hyperextension distal domain, no exhumation sub-domain and outer domain are identified (profiles E and F). The TS5 fault appears as the typical geometry structuring the distalmost and outer domains in the rifted margins (the distal breakaway complex of *Osmundsen et al.*, 2021) that is absent in the North Sea rift. UB upper basement. LRB lower reflective basement.

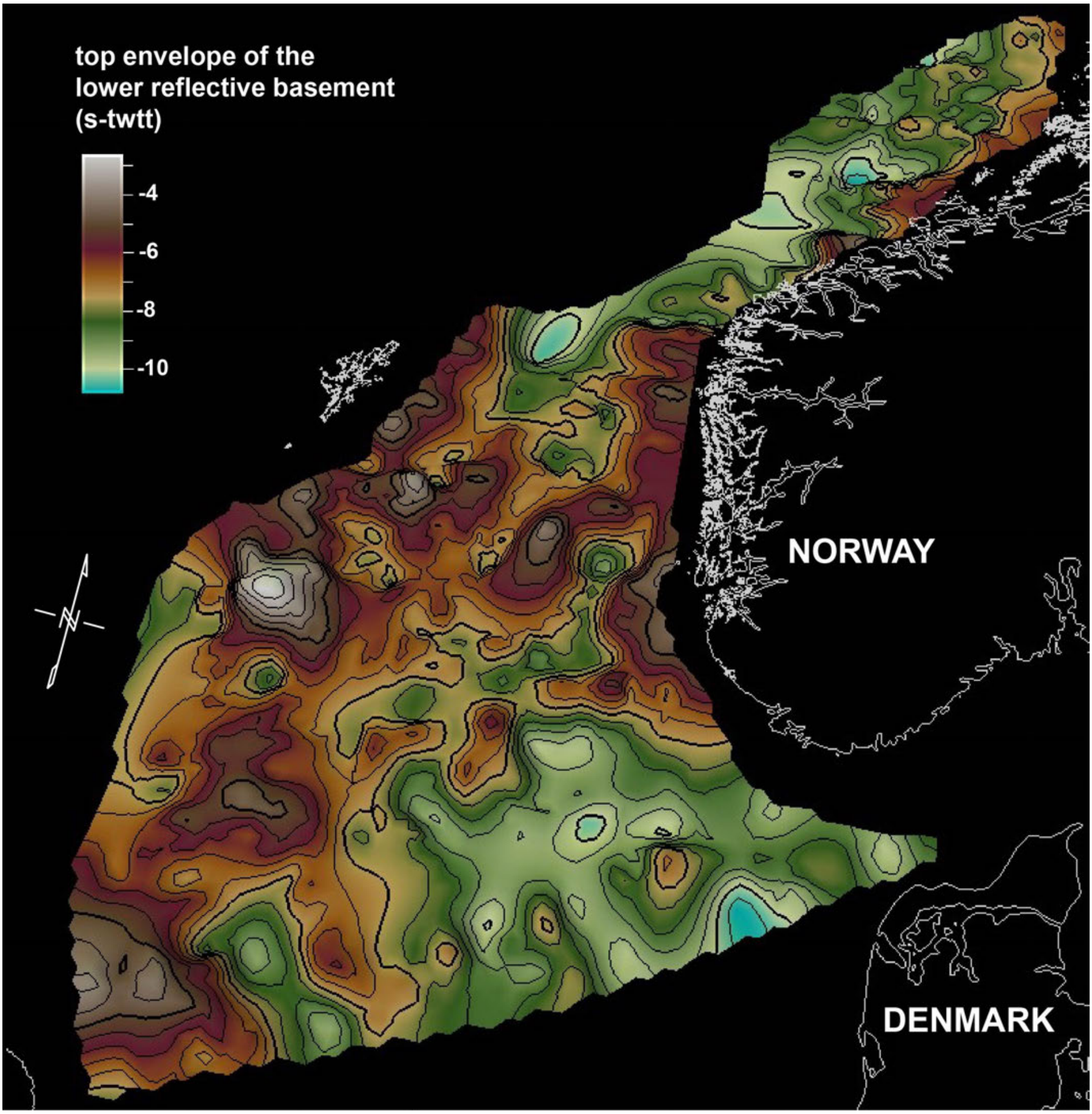


Figure 9 – Perspective view of the gridded surface of the top envelope of the lower reflective basement. s-twtt: seconds two-way-travel-time.

seismic facies and typical partition in two well-defined distinct layers over the entire extensional system. The whole Norwegian extensional system appears to be floored by similar occurrences of transparent upper basement, reflective lower basement, major shear zones (our TS1) and detachment faults (our TS2 and TS3) (Figures 8 and 9). This observation, combined with similar local mapping achieved on the Trøndelag Platform area (*Peron-Pinvidic et al.*, 2020), Føya High (*Gresseth et al.*, 2023), Utsira High (*Serck et al.*, 2022) and observations onshore Norway (e.g., *Osmundsen et al.*, 2003, 2006; *Fossen et al.*, 2017; *Osmundsen et al.*, 2023), suggest that it is probably the all former Caledonian orogenic belt that is characterized by such geometries. Thus, structurally, the Norwegian Continental Shelf settles on an area floored by a mattress of anastomosing mylonitic shear zones forming, at regional scale, a corrugated surface isolating less deformed basement blocks and zones of intense ductile shearing. Figure 9 pro-poses a gridded surface of the mapped top envelope of the TS1 occurrences and lower reflective basement on our dataset. The resolution is low because of the repartition of the profiles, but the map clearly shows the regional extent of the ductily deformed lower crust.

Thus, on that point, no major architectural difference appears between the rift and the rifted margins. The lower basement reflectivity, seismic facies and geometries are com-parable from the rift to the rifted margins (Figure 8). Therefore, the basement may not be considered as main responsible factor in the North Sea case to explain the abandonment of the rift axis, as this latter appears extremely similar to the basement of the adjacent rifted margins. However, the observations reported here are only structural, and the rheology or thermal status of the basement cannot be investigated in this study. Such parameters have been shown to possibly influence rift evolution (e.g., *Huismans and Beaumont*, 2011; *Naliboff and Buiter*, 2015; *Glerum et al.*, 2020) and it is admitted that their variations may play a role in the Norwegian Continental Shelf structural evolution.

5.2 Rift Failure Scenario 2: the Different Reactivation of Inherited Geometries?

Many researchers have studied and demonstrated the influence of the pre-extension lithospheric structuration on rift evolution (e.g., *Capdevila and Mougenot*, 1988; *Wilson et al.*, 1989; *Doré et al.*, 1997; *Osmundsen et al.*, 2002; *Guiraud et al.*, 2010), such as the presence of initial crustal weaknesses which can play a major role in the development and evolution of a fault system (*Dunbar and Sawyer*, 1989; *Bassi*, 1991; *Ziegler and Cloetingh*, 2004; *Dyksterhuis et al.*, 2007; *Corti et al.*, 2007; *Rotevatn et al.*, 2018; *Brune et al.*, 2017).

The North Sea rift is the archetype of a multi-phase rift (Ziegler, 1989), and it has early been proven that the pre-Mesozoic structural lineaments strongly controlled the tectonic evolution of the subsequent rifting (*Bartholomew et al.*, 1993). In that sense, it is often assumed that the fault systems tend to reactivate pre-existing structures instead of cutting through the fabric (*Badley et al.*, 1988). However, detailed mapping of some local fault systems reveal that the inherited structural grain does not systematically govern the geometry and evolution of the subsequent tectonic activity (*Tomasso et al.*, 2008). Based on modern dataset, *Phillips et al.* (2016, 2019) showed for example that structural reactivation can be operated in various manner (merging, cross-cutting, exploitative fault interactions). The extension direction and preferential or non-preferential orientation of the pre-tectonic structural grain play a role, such as the thickness of the basement heterogeneities and their dip (*Phillips et al.*, 2016). Still within the context of the North Sea rift, *Reeve et al.* (2014) have shown that the Late Jurassic fault system of the Måløy Slope area simply truncate and offset the pre-existing fabric without any structural influence of the pre-rift shear zones. The presence of major deformation structures such as shear zones is therefore not a decisive influencing parameter for the subsequent structural evolution of the rift. At larger scale, *Fazlikhani et al.* (2017) have shown that the interaction between the basement shear zones and the later rift faults is highly variable. They suggest that the orientation (strike & dip) relative to the extension direction together with their mechanical proper-ties are the key factors controlling the possible influence.

Once again, for that point, our observations are comparable for the rift and for the rifted margins. In both settings, we observe similar structural relationship and/or opportunistic re-activation of previous structures. TS2 and TS3 faults are for instance interpreted as showing various generation of tectonic activity including de-activation and re-activation of some fault segments, and structural interaction with the TS1 shear zones, notably where they form culminations. On the opposite, TS4 and TS5 structures seem to crosscut the previous fabric without clear reuse of earlier geometries. Figure 10 tentatively summarizes these findings with a schematic cartoon. Similar structural interactions have been observed in the Møre and Vøring rifted margins where successive incisions of faults form complex geometries within the necking domain (*Osmundsen et al.*, 2021). *Gresseth et al.* (2023) demonstrated the geometrical complexity of the necking domain located in the Frøya High region in the Vøring margin. They highlighted the important role played by the combined brittle-ductile deformation and core complexes development in the architectural variations. The TS1-TS2/3 structural relationship observed in this study appear extremely similar to these results, although the resolution of our dataset does not allow similar detailed mapping.

Based on this, it can be concluded that the geometries related to the reactivation of inherited structures are similar in the two contexts of the rift and rifted margins. Thus, structural inheritance may neither be considered as the determining factor in the North Sea case to explain the abandonment of the rift axis. It may play a role at a local scale but seems not to be decisive at regional scale, as structural observations are similar from the rift to the rifted margin.

5.3 Rift Failure Scenario 3: the Fault of the Faults?

In the case of the South China Sea, *Li et al.* (2020) suggested that different rifting process-es led to the formation of different geometrical contexts from one sector to the other with-in a same rift, what influenced the rift failure (e.g., Tainan Southern Depression and the Baiyun Sag; *Li et al.*, 2020). In the Norwegian Continental Shelf case, as summarized above, our regional study reveals no major geometrical difference between the failed and the successful axes. The global architecture, basement seismic facies and structural geometries are similar: After Caledonian orogeny, the northern North Sea lithosphere un-derwent intense crustal

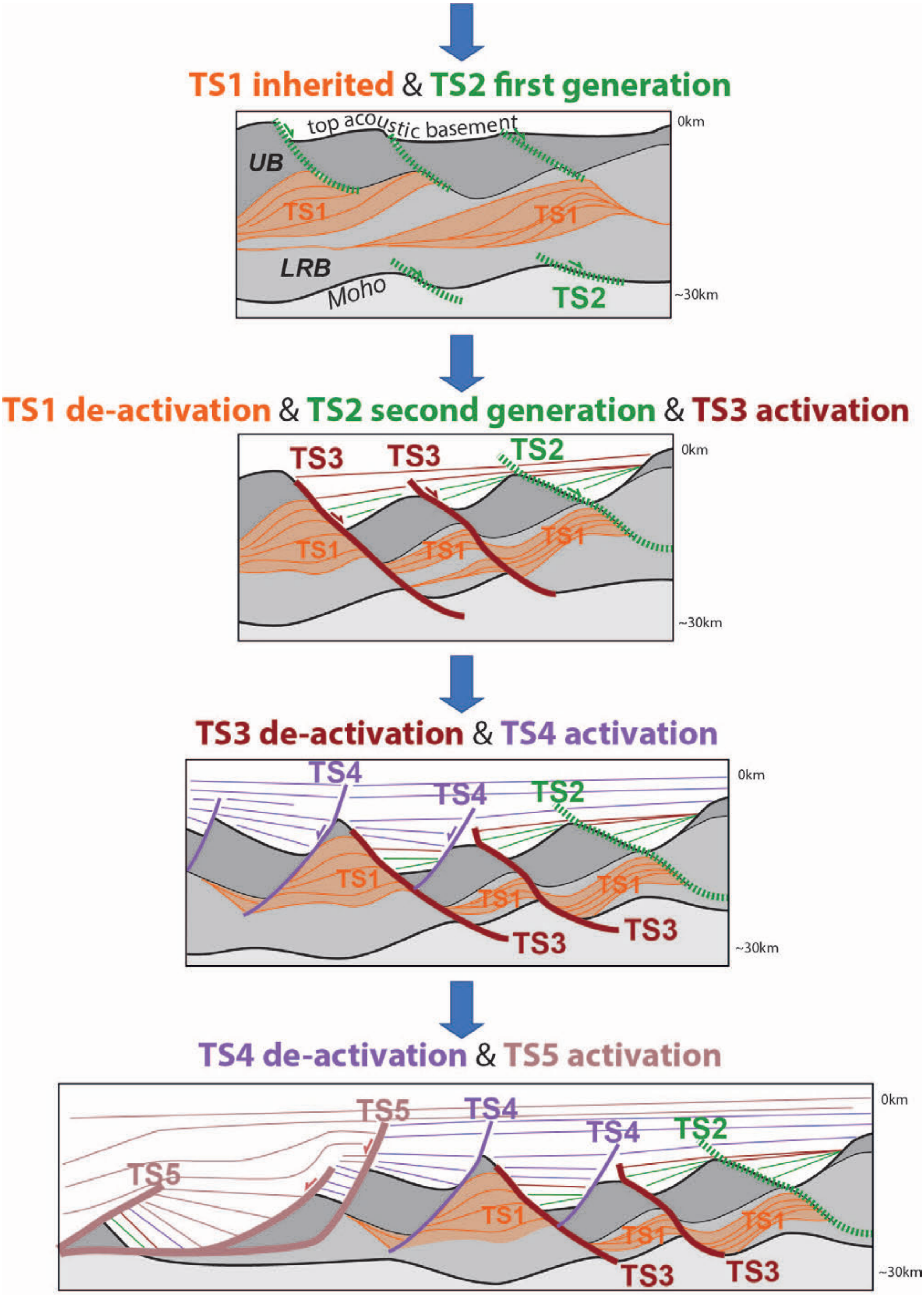


Figure 10 – Schematic cartoon illustrating the five types of tectonic structures (TS1-5) identified on the Norwegian Continental Shelf. The top-down sequence illustrates the potential successive activation, de-activation and re-activation of the various tectonic structures. TS tectonic structure. UB upper basement. LRB lower reflective basement.

reduction, notably by means of ductile deformation (e.g., *Fossen*, 2010). The related mylonitic shear zones have been identified and mapped both onshore and offshore (*Gabrielsen et al.*, 2015; *Fossen et al.*, 2014; *Fazlikhani et al.*, 2017; *Lenhart et al.*, 2019; *Serck et al.*, 2022). In our dataset, they are today recognized in the TS1 occur-rences. These are discontinuous but form at regional scale an undulating mattress that floor the whole rift (Figure 9). Subsequent faults (TS2) cut through the basement and often root on the shear zone corrugations (TS1) with geometries attesting of structural brittle-ductile interactions. Then, TS3 detachment faults permit deformation coupling through the entire basement and form today major structures bounding domains where the basement has been extensively thinned. These North Sea observations are directly comparable to the structural mapping operated on the Møre and Vøring rifted margins. The key observation listed here is that the North Sea rift does not show any occurrence of distal domain breakaway complex (TS5) and outer domain breakaway complex (*Osmundsen and Péron-Pinvidic*, 2018). So, within the rift, the so-called distal domain encompasses only hyperex-tended geometries, and no exhumation-type geometries are observed.

Thus, the North Sea and the Møre and Vøring rift axes shared relatively the same tectonic evolution up to the hyperextension/exhumation deformation stage. Structurally, the North Sea rift failure appears to be associated with the failure to initiate distal domain breakaway complex -type faults (TS5). As the influence of the inherited basement and structures have been ruled out based on the previous discussions (above Sections 5.1 and 5.2), external parameter(s) may be claimed to explain this absence. For instance, the orientation and rate of extension are often listed as determining factors (e.g., *Corti*, 2008; *Heine et al.*, 2013; *Brune et al.*, 2018; *Zwaan and Schreurs*, 2023). Within the context of the North Sea rift, characterized by a long and multi-phase extensional history, the inter-rift periods responsible for drastic extension rate changes, should be considered with care. These phases of relative tectonic quiescence can lead to substantial thermal relaxation and re-equilibration of the lithosphere. Cooling and strengthening of the extended terranes may promote rift jump to areas mechanically more prone to accommodate extension. The inability of the North Sea rift to initiate distal breakaway complexes -type of faults may be related to such lithospheric strength variations. For the northern South China Sea, based on numerical experiments, *Li et al.* (2020) suggested that, although the crust is drastically reduced, the mantle lithosphere may not be thinned enough to allow the development of the next phase of deformation. A similar configuration may be advocated for the North Sea rift case. However, geophysical modelling would be necessary to investigate this scenario to constrain potential variations in the mantle lithosphere thickness.

6 Conclusions

The study summarized here took advantage of a newly released dataset to perform a regional-scale study of the basement geometries and seismic facies variations through the Norwegian Continental Shelf. The deep penetrating seismic reflection profiles allow the observation, mapping, and analysis of the entire basement, including the lower crust, Mo-ho and upper mantle.

The basement seismic facies bipartition, architecture and structural geometries are simi-lar over the whole Norwegian Continental Shelf. Five distinct types of tectonic structures are identified (TS1-5), from thick shear zones to various large-scale detachment faults and local high-angle normal faults. These are interpreted as the major bounding faults re-sponsible for shaping the various structural domains. The main difference between the rift and the rifted margins settings are the TS5-type detachment faults which are only ob-served within the Møre and Vøring margins' distal domains.

Various parameters and combination of parameters can be advocated to explain the failure of a rift to reach breakup. Scenarios related to the thermal state of the lithosphere, rheology of the crust or magma supply are not investigated in this contribution. For the work summarized here, focus is set on geometrical constraints and structural differences and similarities between the rift and the rifted margins. Based on our observations, it is proposed that the North Sea rift and the Møre and Vøring rifted margins probably shared similar pre-rift conditions and comparable rift evolution up to the hyperextension/exhumation deformation stages. Hyperextension geometries are observed in the rift but no distal or outer breakaway complexes (the TS5). External factor(s) such as direction and/or rate of extension, together with variations in the amount of lithospheric thinning are favoured to explain this absence and the abandonment of the North Sea rift in favour of the Møre and Vøring rifted margins.

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Author contributions

GPP performed the study, sketched the figures and wrote the paper. **TÅ** and **LIL** provided the dataset and participated in the discussions.

Data availability

The data that support the findings of this study are the property of Geoex MCG. Restrictions apply to the availability of the profiles, which were used under license for the current study. Geoex MCG should be contacted for any further information and access conditions regarding the data. The interpretation and conclusions summarized in this contribution are based solely on the analysis of the final processed profiles. The additional NSR and MNR dataset are in the public domain and can be requested through the DISKOS database, administered by the Norwegian Petroleum Directorate.

Competing interests

The authors declare no competing interests.

Peer review

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