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Key Points:
- Devonian postorogenic shear zones dip in various directions with <40 degrees in the northern North Sea rift, central part of the Caledonian orogenic belt
- Shear zones with present-day dips higher than ~15° were reactivated during the late Paleozoic-Mesozoic rift events
- Several basement shear zones have been offset by rift-related faults regardless of their orientation relative to the rift extension direction

Correspondence to:
H. Fazlikhani,
hamed.khani@uib.no

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Basement structure and its influence on the structural configuration of the northern North Sea rift

Hamed Fazlikhani[1], Haakon Fossen[1,2], Robert L. Gawthorpe[1], Jan Inge Faleide[3], and Rebecca E. Bell[4]

[1]Department of Earth Science, University of Bergen, Bergen, Norway, [2]Museum of Natural History, University of Bergen, Bergen, Norway, [3]Department of Geosciences, University of Oslo, Oslo, Norway, [4]Basins Research Group (BRG), Department of Earth Science and Engineering, Imperial College London, London, UK

Abstract The northern North Sea rift basin developed on a heterogeneous crust comprising structures inherited from the Caledonian orogeny and Devonian postorogenic extension. Integrating two-dimensional regional seismic reflection data and information from basement wells, we investigate the prerift structural configuration in the northern North Sea rift. Three seismic facies have been defined below the base rift surface: (1) relatively low-amplitude and low-frequency reflections, interpreted as pre-Caledonian metasediments, Caledonian nappes, and/or Devonian clastic sediments; (2) packages of high-amplitude dipping reflections (>500 ms thick), interpreted as basement shear zones; and (3) medium-amplitude and high-frequency reflections interpreted as less sheared crystalline basement of Proterozoic and Paleozoic (Caledonian) origin. Some zones of Seismic Facies 2 can be linked to onshore Devonian shear zones, whereas others are restricted to the offshore rift area. Interpreted offshore shear zones dip S, ESE, and WNW in contrast to W to NW dipping shear zones onshore West Norway. Our results indicate that Devonian strain and ductile deformation was distributed throughout the Caledonian orogenic belt from central South Norway to the Shetland Platform. Most of the Devonian basins related to this extension are, however, removed by erosion during subsequent exhumation. Basement shear zones reactivated during the rifting and locally control the location and geometry of rift depocenters, e.g., in the Stord and East Shetland basins. Prerift structures with present-day dips >15° were reactivated, although some of the basement shear zones are displaced by rift faults regardless of their orientation relative to rift extension direction.

1. Introduction

Rift basins generally develop on structurally and mechanically heterogeneous crust involved in prerifting deformation events and comprise a complex array of brittle faults, fracture networks, ductile shear zones, and penetrative fabrics, often with a large variety of orientations and geometries. Basement heterogeneities may influence the location and geometry of later rift basins, and their control on rift evolution has been a long-standing subject of research in rifts worldwide, for example, in the East African Rift [*Mcconnell*, 1972; *Versfelt and Rosendahl*, 1989; *Ring*, 1994], Gulf of Aden [*Leroy et al.*, 2012], Rhine Graben [*Schumacher*, 2002], the Recôncavo-Tucano-Jatobá Rift [*Milani and Davison*, 1988], and in the Eastern North America [*Swanson*, 1986; *Withjack et al.*, 1998]. The influence of preexisting structures on the geometry and development of rift basins has been studied using scaled analog and numerical modeling techniques [*Corti et al.*, 2007; *Henza et al.*, 2011; *Autin et al.*, 2013; *Brune and Autin*, 2013]. Many authors have concluded that preexisting structures exert a regional-scale control on the location and geometry of rift basin, notably with respect to first-order segmentation pattern. However, at the scale of individual faults and subbasins the relationship between prerift and rift structures may be less clear [*Whipp et al.*, 2014; *Fazli Khani and Back*, 2015; *Phillips et al.*, 2016].

The northern North Sea rift evolved over at least two late Paleozoic-Mesozoic rift phases and was built on a basement that consisted of Proterozoic and Caledonian rocks with variable Caledonian fabrics and Devonian extensional shear zones [*Fossen*, 2010] (Figure 1). These prerift basement structures have been studied in considerable detail onshore Western Norway, northern Scotland, and east Greenland. However, in the northern North Sea, the nature and influence of prerift structures are enigmatic. In this study we integrate two-dimensional deep (15 s two-way time (TWT)) and commercial (9 s TWT) seismic data and 72 basement wells, covering the entire northern North Sea rift basin (Figure 2) to establish an understanding of the prerift

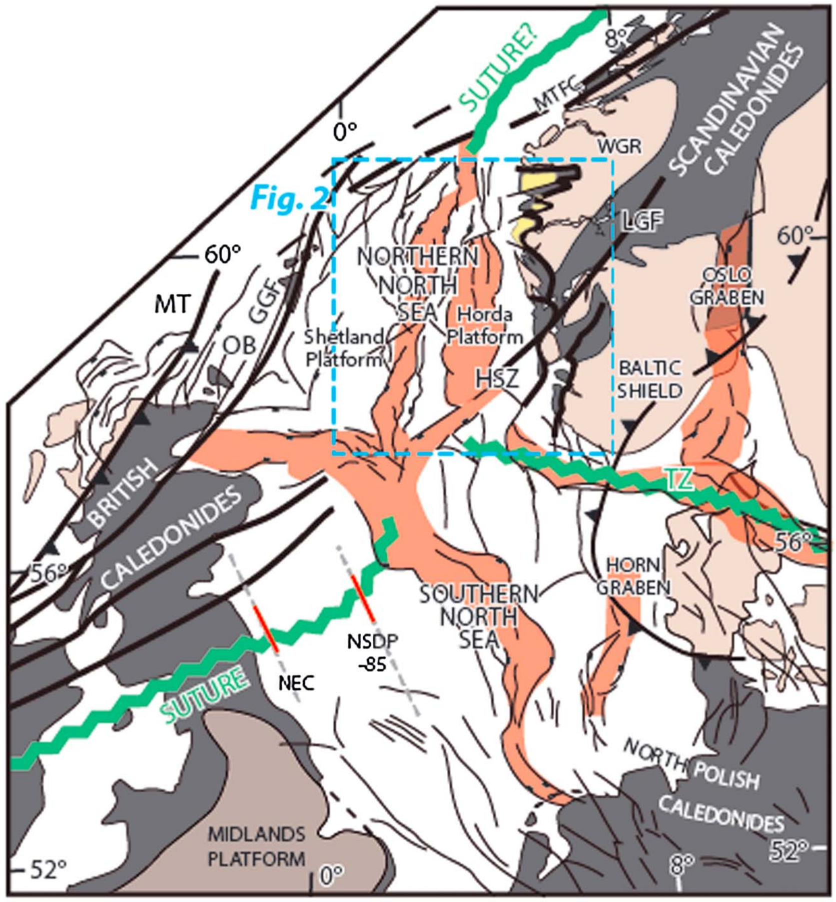

Figure 1. Geological setting of the North Sea rift and its margins. Areas highlighted by red show the main Late Paleozoic-Mesozoic rift axes. HSZ, Hardangerfjord Shear Zone; LGF, Lærdal-Gjende Faults; MTFC, Møre-Trøndelag Fault Complex; TZ, Tornquist Zone; WGR, Western Gneiss Region; MT, Moine Thrust; OB, Orcadian Basin; GGF, Great Glen Fault. Note that the precise location of the suture zone is not known in the northern North Sea area. NSDP85 and NEC are deep seismic sections used to locate the suture zone offshore eastern UK [from *Freeman et al*., 1988].

structural and lithological configuration, and discuss its influence on the rift development in the northern North Sea area.

2. Geological Setting

The northern North Sea rift developed mainly as a result of a Late Permian-Early Triassic extension phase followed by thermal cooling and subsidence from the Early-Middle Triassic to Middle Jurassic, and a Middle-Late Jurassic to Early Cretaceous extension phase followed by Cretaceous postrift subsidence [*Badley et al*., 1988; *Gabrielsen et al*., 1990; *Ziegler*, 1990; *Underhill and Partington,* 1993, 1994; *Færseth*, 1996; *Odinsen et al*., 2000; *Lervik*, 2006]. The northern North Sea rift basin developed on a highly heterogeneous basement that experienced Caledonian orogenic deformation and Devonian postorogenic extension [*Færseth*, 1996; *Odinsen et al*., 2000; *Fossen et al*., 2016]. The Caledonian orogeny generated a classical thin-skinned thrust tectonic architecture in the foreland part of the orogen, and gradually more basement involved (thick-skinned) deformation toward the hinterland northwest of the Hardangerfjord Shear Zone (HSZ, Figure 1) [*Milnes et al*., 1997; *Fossen et al*., 2014]. The allochthonous units comprise nappes of continental margin affinity (Lower and Middle Allochthon) overlain by units of outboard (oceanic) affinity (Upper Allochthon), with a weak basal thrust zone commonly referred to as the basal décollement zone. Subsequent crustal stretching in the Devonian involved reactivation of Caledonian thrusts, notably the basal décollement, as low-angle extensional shear zones (Mode I extension), and secondary extensional shear zones that transect the décollement zone and affect large portions of the Caledonian crust (Figure 1) (Mode II extension) [*Fossen*, 1992, 2010].

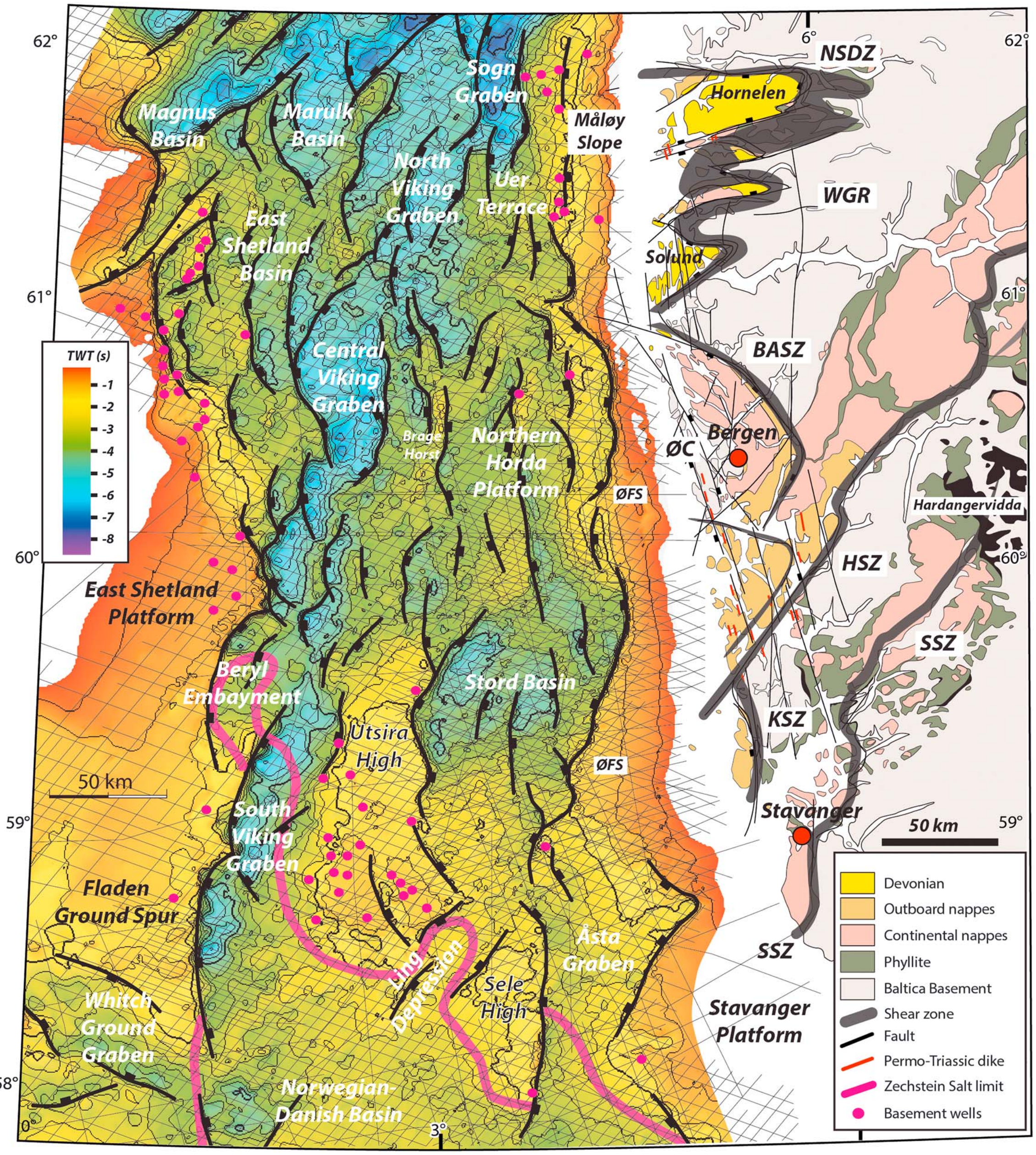

Figure 2. The base rift surface (base Permo-Triassic rifting) time-structure map in the northern North Sea rift and the geology of southwestern Norway, showing the general onshore and offshore structural configuration in the study area. Bold black lines highlight major rift-related normal faults displacing the base rift surface where all units older than Upper Permian is considered basement. Black lines in the background show some of the 2-D seismic reflection surveys used in this study. NSDZ, Nordfjord-Sogn Detachment Zone; BASZ, Bergen Arc Shear Zone; WGR, Western Gneiss Region; ØC, Øygarden Complex (gneiss); ØFS, Øygarden Fault System; HSZ, KSZ, and; SSZ: Hardangerfjord, Karmøy, and Stavanger shear zones, respectively. Note that not all of the basement wells in the Utsira High are shown.

Associated with these shear zones was the development of Devonian basins [*Steel et al.*, 1985], of which several are preserved along the coast of West Norway where they form supradetachment basins in the hanging wall of the Nordfjord-Sogn Detachment Zone (NSDZ) [*Séranne and Séguret*, 1987; *Vetti and Fossen*, 2012] (Figure 1). Besides the décollement zone at the base of the orogenic wedge, the extensional NSDZ is the single most profound extensional shear zone in the Scandinavian Caledonides, with a 5–6 km thick mylonite zone that involved displacements on the order of 100 km [*Norton*, 1987; *Andersen and Jamtveit*, 1990; *Fossen*, 2000; *Fossen et al.*, 2016]. The zone has a gentle westerly dip, but its folded appearance about *E-W* axes causes local steep dips to the north and south. Its northern extension is not clear, but it is generally assumed to be connected with the Devonian precursor of the Møre-Trøndelag Fault Complex to the north and the Bergen Arcs Shear Zone (BASZ) to the south. However, the latter implies a rapid loss of displacement across Sognefjorden, from >50 to 15 km in the northern BASZ, and it may well be that a branch of the NSDZ is located west of the Sotra-Øygarden area west of Bergen [*Fossen*, 1992].

The HSZ is longer than the NSDZ, even though its displacement is considerably smaller (~15 km, Figure 1). Deep seismic data show that the HSZ transects much of the crust, and its seismic signature and onshore expression are consistent with a 25° dip to the NW and a thickness of ~5 km [*Fossen and Hurich*, 2005]. Several authors have suggested that it extends far into, if not across the North Sea rift, based on the structural pattern of the rift and gravimetric and magnetic data [*Hurich and Kristoffersen*, 1988; *Færseth*, 1996; *Andersen et al*., 1999; *Fossen and Hurich*, 2005]. The Karmøy Shear Zone (KSZ) is linked to the HSZ near the coast and is, together with the BASZ, relatively steep. All of the major onshore extensional shear zones contain brittle faults that reveal reactivation under upper crustal conditions. Brittle faults in general show a wide range in orientation, and recent isotopic dating of fault rocks suggests that they have been active repeatedly since the Devonian [*Fossen et al*., 2016; *Ksienzyk et al*., 2016]. The Carboniferous-Early Permian extension as a result of post-Variscan orogenic collapse and the following thermal subsidence led to the development of a southern and a northern Permian basin, containing mainly continental sandstones of the Rotliegend Group overlain by Late Permian Zechstein evaporites [*Ziegler*, 1992]. Zechstein evaporites extend into the southern part of the study area in the South Viking Graben, Ling Depression, and the southern part of the Åsta Graben (Figure 2).

Along the western margin of the northern North Sea rift basin, northern Scotland, and its northeastern offshore areas (Figure 1), Devonian structures are mainly represented by large-scale listric normal faults. In the offshore area these Devonian normal faults appear to detach onto or close to 10–15° dipping reflections interpreted as Caledonian thrusts [*Brewer and Smythe*, 1984; *Mcgeary and Warner*, 1985; *Cheadle et al*., 1987; *Coward et al*., 1989; *Snyder*, 1990; *Bird et al*., 2015]. In the Orcadian Basin and the West Orkney Basin east and west of the Great Glen Fault (Figure 1), very thick (6–7 km) continental Devonian sediments are preserved in large half-grabens [*Norton et al*., 1987; *Coward*, 1990; *Wilson et al*., 2010]. The East Shetland Platform, however, is considered as the northern extension of the Orcadian Basin, where the thickness of Devonian sediments decreases toward the east and northeast, and pinches out close to the major northern North Sea bounding faults [*Platt*, 1995; *Platt and Cartwright*, 1998]. The geometry and the extent of Caledonian and Devonian ductile and brittle structures in the East Shetland Platform as the western margin of northern North Sea rift is poorly documented.

The first rift phase in the northern North Sea is claimed to have initiated in the Late Permian and extended into the Early Triassic [*Steel and Ryseth*, 1990; *Færseth et al*., 1995]. In the southern part of the study area, in the South Viking Graben, Åsta Graben, and Ling Depression rift succession covers the underlying Middle to Late Permian evaporites (and locally some Devonian and Carboniferous sediments), while farther north in the northern Horda Platform and East Shetland Basin, the rift system overlays Caledonian crust and remnants of Devonian basins. The first rifting phase was followed by a second rifting event during the Middle-Late Jurassic to Early Cretaceous, during which phase 1 faults were partly reactivated and the Viking Graben developed as a dominant central graben structure [*Færseth*, 1996; *Odinsen et al*., 2000; *Whipp et al*., 2014; *Bell et al.*, 2014].

3. Data and Methods

This study is based on the compilation of 29 two-dimensional (2D) seismic reflection surveys acquired in the northern North Sea (thin black lines, Figure 2 and Table 1). Seismic lines strike in different directions with line spacing of less than 3 km except for some parts of the East Shetland Platform where the line spacing is about 6 km, allowing for imaging of crustal structures down to 9 s TWTT. An advantage of utilizing numerous seismic surveys acquired with different acquisition methods and processing parameters is that it allows for a better distinction between seismic artifacts and real intrabasement structures. The majority of the 2-D lines utilized in this study cross the entire study area and their good quality and reasonably high density enabled us to identify and confidently map the lateral and vertical extent of regional-scale crustal structures in the northern North Sea rift. Most seismic lines start ~10 km off the Norwegian coast, close enough to allow for offshore-onshore correlation of first-order structures. The data set also includes 72

Table 1. Summary of Seismic Data and Their Acquisition Parameters Used in This Study

Seismic Survey	Acquisition Date	Length (km)	Source Interval (m)	Streamer Length \Separation (m)	Sample Interval (ms)	Record Length (s)
CNST-86	1986	5,764	25	3,000	4	7
CNSTE-N-83	1983	800	25	3,000	4	7
EL-9202	1992	307	25	-	4	6
GLD-92	1992	1,287	25	-	4	7
GNSR-91	1991	11,322	25	-	4	9
GSB-85	1985	4,082	25	-	4	7
HPS-98	1998	2,643	25	-	4	6
HRT-93	1993	1,390	25	-	4	7
HT-91	1991	224	25	-	4	7
NNST-84	1984	8,099	25	3,000	2	7
NNSTI-86	1986	684	25	3,000	2	7
NNSTI-87	1987	613	25	3,000	2	7
NSDP-84	1984	1,689	25	-	4	15
NSR-03-12	2003–2012	244,417	25	1 × 7,950\8,100	2	9.2
NVGT-88	1988	3,611	25	-	4	7
NVGTI-92	1992	3,158	25	-	4	7
SBGS-94RE	1994	2,584	25	-	4	7
SG-8043	1980	545	25	-	4	7
SG-8146	1981	2,063	25	-	4	7
SG-9009	1990	567	25	-	4	7
SG-9617	1996	1,273	25	-	4	7
SH-8001	1980	3,950	25	-	4	5
ST-8107WE	1981	166	25	-	4	5
ST-8201-8301	1982–1983	6,182	25	-	4	6
ST-8408	1984	4,261	25	-	4	7
ST-8503	1985	2,761	25	-	4	7
ST-8620	1986	704	25	-	4	7
ST-8703	1987	75	25	-	4	7
TE-90	1990	1,814	25	-	4	6

wells drilled into the basement (Table 2 and Figure 2). These basement wells are mainly located on the marginal parts of the rift, e.g., in the Måløy Slope, Horda Platform, and Stavanger Platform in the east, and in the eastern margin of the East Shetland Platform and the western side of the East Shetland Basin (Figure 2).

Within the basin, crystalline basement rocks have been drilled on basement highs such as the Utsira High, or at the crest of major rotated fault blocks. This well information has been used as tie points for the base rift horizon on the seismic sections that allowed mapping of this surface in the study area. All units beneath the Late Permian-Early Triassic (rift phase 1) rift fill are in the following considered as basement, including Permian sandstones and evaporites, Devonian (meta)sediments, and Caledonian and pre-Caledonian crystalline rocks. Depth conversion of intrabasement structures is carried out using check shot data from exploration wells for the rift fill (Figure 3). Below the base rift surface, depth conversion is based on the velocity model constrained in the northern North Sea using multichannel seismic surveys and several wide-angle expanding spread profiles [*Christiansson et al.*, 2000] and ocean bottom seismometer profiles [*Rosso*, 2007].

4. The Base Rift Horizon and Basement Seismic Facies

Interpretation of the Base Rift horizon is based on the seismic reflectivity appearance of the prerift crust and is tied to 72 basement wells (Figure 2). This surface represents the boundary between Late Permian-Early Triassic rift-related deposits and prerift units, including Permian sandstones and evaporites (e.g., in the Åsta Graben, Ling Depression, and South Viking Graben), Devonian-Carboniferous rocks and structures (e.g., on the Sele High and East Shetland Platform), and Caledonian nappe units (e.g., in the Utsira High and Måløy Slope). Interpretation of intrabasement structures and units (below base rift surface) is based on the definition of the three main seismic facies. Each seismic facies is defined based on their seismic

Table 2. Exploration Wells Penetrating the Prerift Rock Units in the Northern North Sea Rift Used in This Study[a]

Well Name	Top Basement (MD,KB), m	Drilled Thickness (m)	Basement Rock Type	Interpretation
8,3-1	2965	50	Schist	Caledonian allochthon
15,5-3	4850	200	Shale, siltstone, and sandstone	Devonian
16,1-2	2912	25	Granite pink	Caledonian allochthon
16,1-3	3440	57	Granite	Caledonian allochthon
16,1-4	1864	146	Hornblende-gabbro	Caledonian allochthon
16,1-5	2265	194	Granite	Caledonian allochthon
16,1-12	1913	142	Granodiorite	Caledonian allochthon
16,1-15	1920	230	Granite/granodiorite	Caledonian allochthon
16,1-17	1988	82	Felsic, extremely weathered	Caledonian allochthon
16,1-18	2360	31	Granite	Caledonian allochthon
16,1-19	1891	104	Unknown	-
16,2-1	1873	33	Metamorphosed gneissic-granite	Caledonian allochthon
16,2-3	1894	9	Unknown	-
16,2-4	1879	121	Granodiorite	Caledonian allochthon
16,2-5	2342	31	Unknown	-
16,2-9	1986	96	Unknown	-
16,2-12	1939	128	Granite	Caledonian allochthon
16,2-17B	2133	67	Granite	Caledonian allochthon
16,2-18S	1864	106	Granite	Caledonian allochthon
16,2-19	1989	34	Granite	Caledonian allochthon
16,2-20	2183	32	Granite	Caledonian allochthon
16,3-2	2006	12	Monzogranite	Caledonian allochthon
16,3-4	1940	80	Monzogranite	Caledonian allochthon
16,3-6	1965	85	Granodiorite	Caledonian allochthon
16,3-7	2089	11	Granite	Caledonian allochthon
16,4-1	2885	44	Micaschist and granite	Caledonian allochthon
16,4-5	1898	122	Granodiorite	Caledonian allochthon
16,5-1	1925	20	Granodiorite and migmatite	Caledonian allochthon
16,6-1	2055	6	Dacite underlain by metamorphic schist	Caledonian allochthon
17,3-1	2811	41	Green schist	Caledonian allochthon
17,12-2	2300	34	Sandstone	Devonian
18,11-1	2060	26	Quartzite with chloritoschiste	Caledonian allochthon
25,6-1	2851	30	Metamorphosed granite and gneiss	Caledonian allochthon
25,7-1S	3551	41	Metasandstone and chlorite schist	Pre-Caledonian metasediment
25,10-2R	3152	29	Quartz-monzonite/schist anhydrite	Caledonian allochthon
25,11-1	2391	68	Gneissic schist overlaid by siltstone and sandstone	Caledonian allochthon/ Devonian
25,11-17	2243	13	Phyllite	Basal décollement?
25,12-1	2425	440	Conglomerate and sandstone	Devonian
31,6-1	4014	56	Augengneiss overlaid by quartzitic sandstone	Pre-Caledonian metasediment
32,4-1	3132	54	Conglomerate (granitic) and Sandstone	Devonian?
35,3-2	4168	232	Green Mica schist/gneiss	Caledonian allochthon
35,3-4	4069	20	Green Mica schist/gneiss	Caledonian allochthon
35,3-5	4092	22	Green Mica schist/gneiss	Caledonian allochthon
35,9-1	2314	36	Green Mica schist/gneiss	Caledonian allochthon
35,9-2	2856	29	Green Mica schist/gneiss	Caledonian allochthon
35,9-3	2770	13	Metaquartzite and metamorphic	Pre-Caledonian metasediment
36,1-1	1568	27	Augengneiss	Proterozoic basement?
36,1-2	3233	22	Schist	Caledonian allochthon
36,4-1	2712	5	Greenschist	Caledonian allochthon
36,7-1	2834	7	Gneiss	Caledonian allochthon
36,7-2	1429	6	Greenschist	Caledonian allochthon
2-10a-10	1700	20	No data	-
2-10a-11	2225	22	No data	-
2-10a-12	2494	25	No data	-
2-10a-13	2562	18	No data	-
2-10a-6	1694	52	Schist and gneiss	Caledonian allochthon

Table 2. (continued)

Well Name	Top Basement (MD,KB), m	Drilled Thickness (m)	Basement Rock Type	Interpretation
2-10a-7Z	1809	35	Schist and gneiss	Caledonian allochthon
2-10a-8	2734	229	Mica schist and gneiss	Caledonian allochthon
2-10b-5	1343	25	Gneiss or sheared granite	Caledonian allochthon
2-10b-9	1331	31	Gneiss	Caledonian allochthon
2-15-1	1725	28	Schist and gneiss	Caledonian allochthon
2-15a-9	1628	17	Gneiss	Caledonian allochthon
2-20-1	1124	33	Gneiss	Caledonian allochthon
2-3-1	714	50	? Metamorphic	Caledonian allochthon
2-4-2	2335	19	Psammitic metamorphics (Metasandstone)	Devonian?
2-5-10	2610	41	Gneiss	Caledonian allochthon
2-5-11	2919	22	Gneiss	Caledonian allochthon
2-5-4	4131	13	Serpentinite	Caledonian allochthon
211-16-1	3330	21	Granite?	Caledonian allochthon
211-21-1A	3443	27	*Gneiss	Caledonian allochthon
211-21-2	3468	43	*Gneiss	Caledonian allochthon
211-26-1	3254	21	*Gneiss-Schist	Caledonian allochthon
211-26-2	3381	32	*Metasandstone	Devonian?
211-26-3	3509	72	*Metasandstone	Devonian?
3-11-1	2126	16	Granitic Gneiss	Caledonian allochthon
3-11-2	2520	19	Granite	Caledonian allochthon
3-11a-6	1981	33	Granite	Caledonian allochthon
3-11b-7	1891	29	*Granite	Caledonian allochthon
3-21-1	1989	18	Mica, gneiss, and schist	Caledonian allochthon
3-3-4ARE	4407	36	*Gneiss	Caledonian allochthon

[a]Depths are Measured Depth (MD) from the Kelly Bushing (KB). Well information indicated by asterisk is from *Bassett* [2003] and *Marshall and Hewett* [2003].

appearance and is distinguishable throughout the study area despite the fact that the data set includes several 2-D seismic surveys with various acquisition and processing conditions.

4.1. Top Acoustic Basement and Base Rift Interpretation

The top of the acoustic basement is mainly represented by a single, very high amplitude and high frequency reflection that separates subhorizontal or gently dipping subparallel reflections from sedimentary units from underlying reflections with variable amplitudes, orientations, and geometries (Figure 4a). The top acoustic basement is particularly reflective in the platform areas and basement highs, e.g., in the Horda Platform, Stavanger Platform, Utsira High, and in the western side of the East Shetland Basin (Figures 2 and 4a). At these locations, the top acoustic basement surface represents the base of the first rift phase. Away from deep wells penetrating into the basement units and in the deeper parts of the basin, e.g., the Viking Graben, west side of the East Shetland Basin, and the Stord Basin, the interpretation is based on the seismic reflection facies. Thus, the offshore time-structural map in Figure 2 shows the structural configuration of the northern North Sea rift at the base rift level. Below this surface the reflective expression of the basement is subdivided into three different seismic facies.

4.2. Seismic Facies 1

Seismic Facies 1 is characterized by low- to medium-amplitude, semicontinuous, low-frequency, and mainly hummocky reflections that in places appear semitransparent and chaotic (Figure 4b). Reflections within Seismic Facies 1 at some locations are subparallel to the overlying base rift surface and form a zone of variable thickness that can reach to up to 2 s TWT. Seismic Facies 1 is observed in-between two or more sets of dipping high-amplitude reflections of Seismic Facies 2 and/or between the base rift surface and Seismic Facies 2 (Figure 5a). The lower boundary of this seismic facies is marked by a very high amplitude reflection when not bounded only by Seismic Facies 2 (Figure 5b). Units of Seismic Facies 1 are laterally displaced and at some locations rotated by rift-related normal faults (Figure 5c). Seismic Facies 1 has been drilled by several

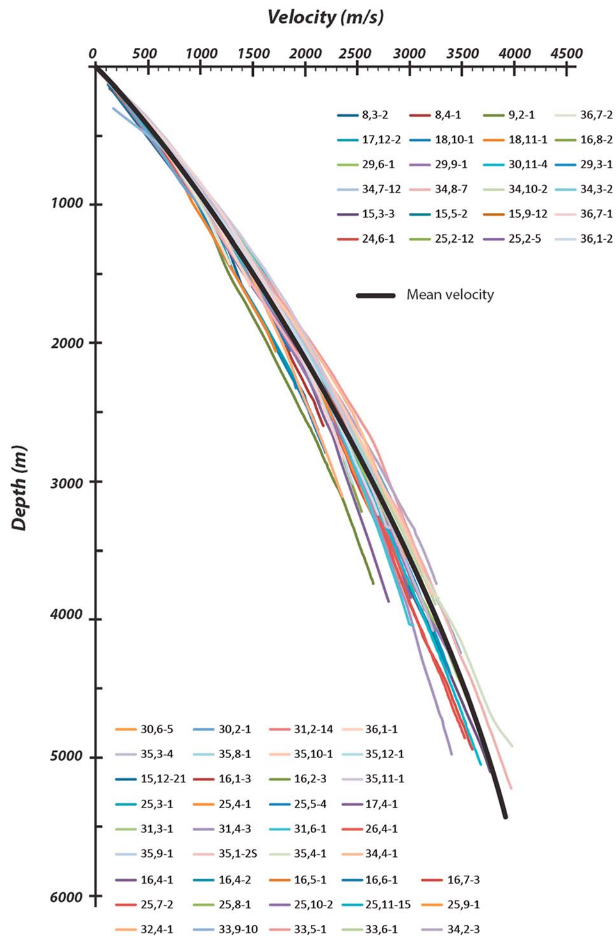

Figure 3. Time-depth relationships in the sedimentary cover used in domain conversion. In the basement time-depth relationship is based on the published seismic refraction and expanding spread profiles (ESP) [*Christiansson et al.*, 2000; *Rosso*, 2007].

wells in the northern North Sea area. In the Måløy Slope area well 35/9-3 (see Figure 6 for location) encountered quartzitic units, while about 10 km to the south, well 35/9-1 penetrated a green micaschist typical for the upper Caledonian allochthon (outboard nappes in Figure 2). Four kilometers to the southeast, well 36/7-1 encountered gneiss (Figure 6 and Table 2). However, each well only penetrates the basement by a few meters in most cases, and it is therefore difficult to tell if the encountered lithologies are representative for this seismic facies as a whole. The coast-parallel deep seismic profiles ILP10 and 11 [*Færseth et al.*, 1995; *Hurich*, 1996; *Gabrielsen et al.*, 2015] show some transparent and low-frequency areas above dipping high-amplitude reflection packages interpreted to represent the Hardangerfjord Shear Zone and Nordfjord-Sogn Detachment Zone. These units were interpreted as Caledonian allochthons and possibly Devonian metasediments, which support an interpretation of Seismic Facies 1 as representing Caledonian nappe units or Devonian metasediments. However, it is difficult to distinguish between different lithological and tectonostratigraphic units away from basement wells based on seismic signature alone.

4.3. Seismic Facies 2

Seismic Facies 2 is characterized by mainly high-amplitude and subparallel reflections that form 500–1000 ms thick packages of reflections dipping in different directions (Figure 4c). Seismic Facies 2 can be traced downward into the middle and locally into the lower crust (≥8 s TWT) and is in places, truncated by the base rift surface (Figure 4a). Similar packages of high-amplitude and continuous reflections have previously been observed along the coast of West Norway [ILP lines, *Færseth et al.*, 1995; *Hurich*, 1996] and the northern

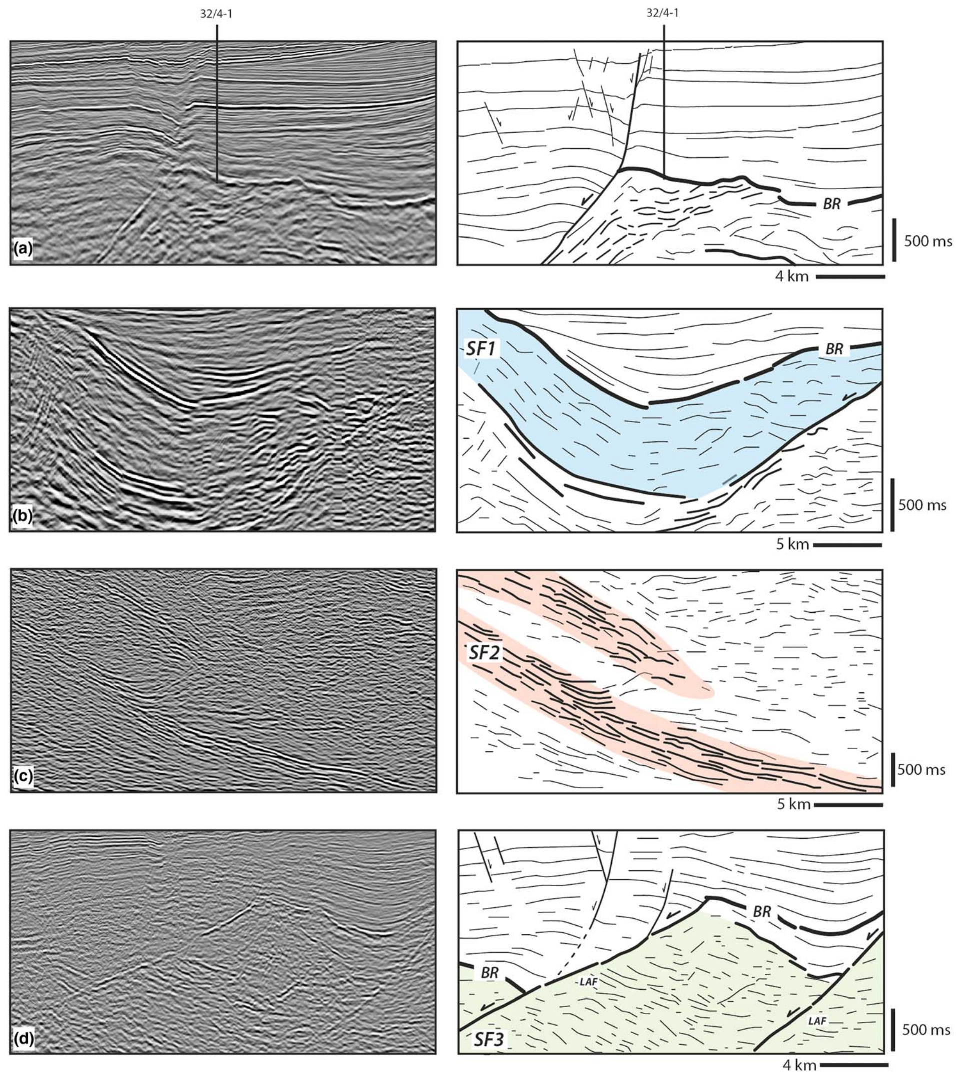

Figure 4. The base rift surface (BR) and three main Seismic Facies (SF1–SF3) used to categorize the seismic data in the study area. (a) The BR surface separates rift deposits form underlying dipping reflections. This surface coincides with the top of the offshore basement units (Baltican crust, Caledonian nappes, and Devonian metasediments). (b) Seismic Facies 1 (SF1) is bounded upward by the BR surface and downward or lateraly by a high-amplitude reflections of SF2. (c) Seismic Facies 2 (SF2) is characterized by a thick package (up to 1000 ms, TWT) of high-frequency and high-amplitude dipping reflections. In some areas, SF2 is truncated by the BR surface. (d) Seismic Facies 3 (SF3) is the most common facies in the study area and characterized by medium amplitude and chaotic to semicontinuous reflections. Thin (<30 ms) dipping high-amplitude reflections interpreted as brittle low-angle faults (LAF) rotate the hanging wall reflections.

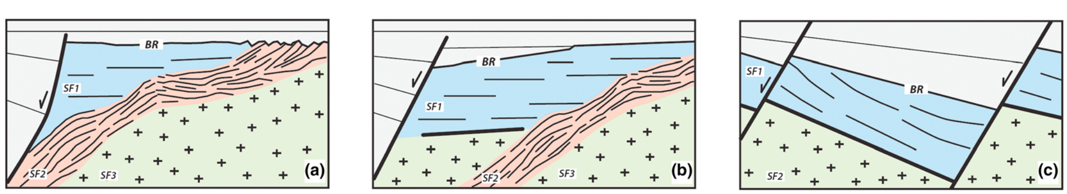

Figure 5. Generalized cartoon showing the relationships between Seismic Facies 1, 2, and 3. (a) Seismic Facies 1 is laterally and vertically bounded by high-amplitude reflections of Seismic Facies 2 and displaced by rift-related normal fault. (b) Seismic Facies 1 reflections laterally bounded to Seismic Facies 2 and displaced by rift-related normal fault; at depth it is bounded by a high-amplitude reflection. (c) Seismic Facies 1 reflections are rotated by rift-related normal faults and bounded by a high-amplitude reflection at depth.

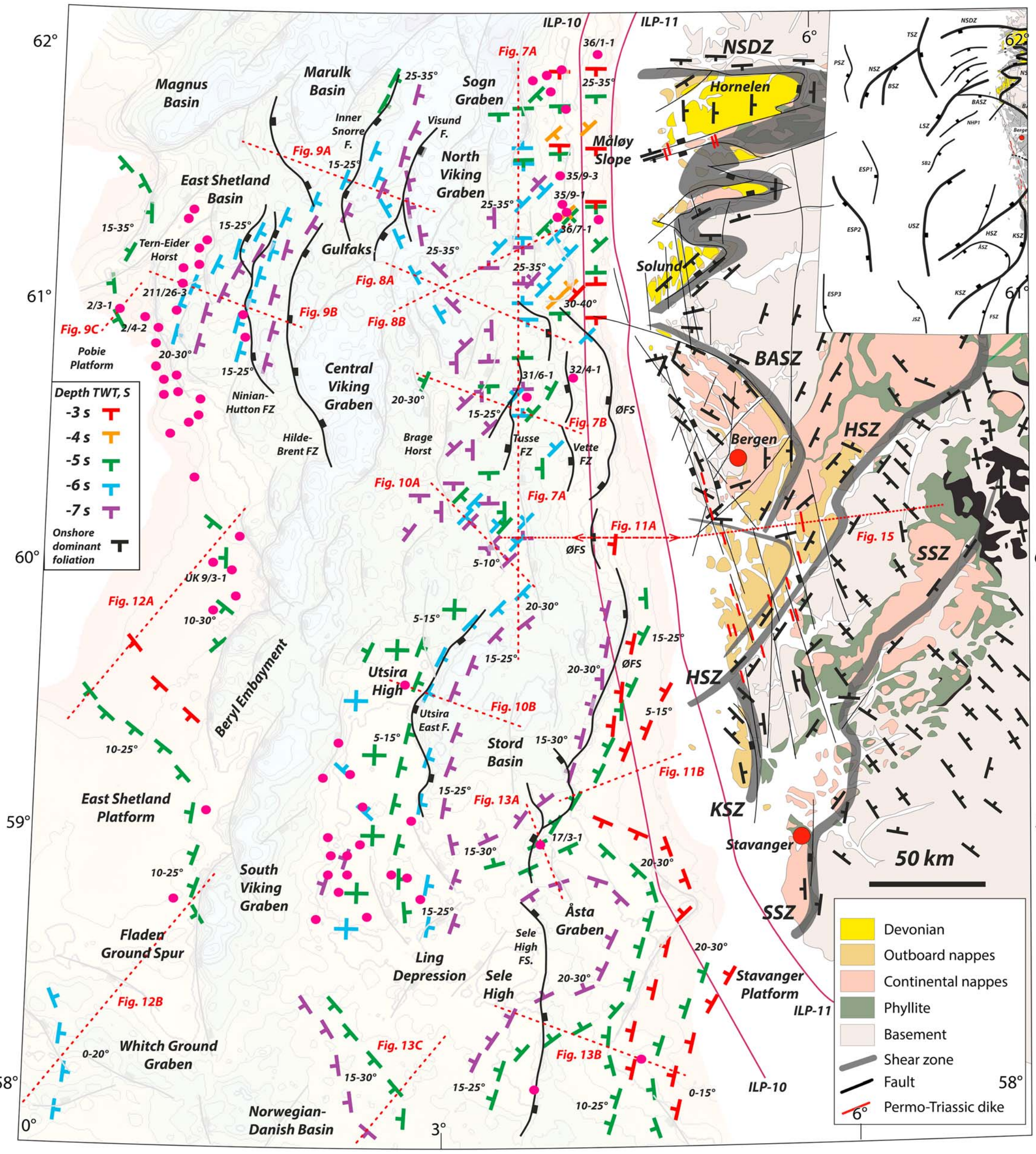

Figure 6. Depth (TWT), strike, and dip of high-amplitude Seismic Facies 2 reflections in the northern North Sea rift. The upper boundary of each reflection package has been used for depth conversion and dip measurements. Dashed red lines show the location of vertical cross sections. Inset map shows the plan view geometry of interpreted highly strained and sheared zones in the northern North Sea area and their relationships to the onshore shear zones. Abbreviations in the inset map are NHP1, North Horda Platform 1; SB2, Stord Basin 2; ESP1, 2, and 3, East Shetland Platform 1, 2, and 3; PSZ, TSZ, NSZ, BSZ, LSZ, ÅSZ, USZ, JSZ, and FSZ are Pobie, Tampen, Ninian, Brent, Lomre, Åsta, Utsira, Jaeren, and Flekkefjord shear zones, respectively. Pink circles show the location of basement wells. Some of the major basin-bounding rift faults are shown as black lines.

Apennines, central Italy [*Brogi et al*., 2003]. Such reflection packages have been interpreted as zones of highly strained and sheared material within the crust, i.e., ductile shear zones. However, in the easternmost Scandinavian Caledonides very strong reflections within the basement have also been interpreted as dolerite intrusions [*Hedin et al*., 2012]. Hence, the high-amplitude reflection pattern in the North Sea basement could also represent dike swarms, although the fact that many of them define zones of only a few kilometers thickness with dips (<45°) and geometry similar to shear zones mapped onshore suggests that they represent Devonian extensional shear zones. Very shallowly dipping (<10°) reflections of Seismic Facies 2 can also be interpreted as the basal décollement and upper parts of the Proterozoic basement involved in the

Caledonian deformation [*Phillips et al*., 2016]. On the eastern side of the study area the majority of Seismic Facies 2 has been linked to onshore Devonian shear zones [*Hurich and Kristoffersen*, 1988; *Færseth et al*., 1995; *Hurich*, 1996; *Fossen et al*., 2016; *Phillips et al*., 2016; and this study]. Hence, similar seismic signatures elsewhere in the northern North Sea are also likely to represent Devonian shear zones with internal mylonitic fabrics.

4.4. Seismic Facies 3

Seismic Facies 3 is the most common seismic facies below the base rift surface in the study area and is characterized by medium-amplitude, semicontinuous, and high-frequency reflections (Figure 4c). Seismic Facies 3 is mainly observed below Seismic Facies 1 and only locally reaches the base rift surface. Close to the base rift surface and the reflections of Seismic Facies 1, Seismic Facies 3 comprises dipping and higher-amplitude reflections. Seismic Facies 3 envelopes Seismic Facies 2 in the middle and lower crust and extends to the lower limit of the data set at 9 s TWT. Considering that Seismic Facies 1 and Seismic Facies 2 are interpreted to represent metasediments, Caledonian nappes, and Devonian shear zones, Seismic Facies 3 is interpreted as Proterozoic basement. In the Caledonian foreland seismic basement reflections with characteristics similar to Seismic Facies 3 characterize Proterozoic basement [*Hedin et al*., 2012; *Juhlin et al*., 2016].

Within Seismic Facies 3, some high-amplitude and semicontinuous thin (<30 ms thick) basement reflections are observed (e.g., Figure 4d). These reflections are mostly dipping <40° to the west in the Horda Platform and to the east in the western flank of the Viking Graben and are interpreted as low-angle brittle faults within the basement. The low-angle basement faults displace the base rift surface at some locations and affect only the lower parts of the rift fill. Steeper normal faults in the synrift fill typically sole out on top of these low-angle normal faults, possibly reactivating the entire structure or only some portion of underlying low-angle normal faults and shear zones (Figure 4d).

5. Interpretation of Intrabasement Structure

The seismic facies classification described above was utilized to map the intrabasement structure in the northern North Sea rift. In order to better describe the basement structures, the study area is subdivided geographically into five subregions: (1) the Måløy Slope and northern Horda Platform, (2) Tampen Spur and East Shetland Basin, (3) Stord Basin and Ustira High, (4) East Shetland Platform, and (5) Åsta Graben and Sele High (Figure 2).

5.1. Måløy Slope and Northern Horda Platform

The Måløy Slope and Uer Terrace are located north of 61°N, on the eastern side of the North Viking Graben and Sogn Graben, and west of the onshore Devonian basins of West Norway (Figures 2 and 6). The acoustic basement is relatively shallow (<2 s TWT) close to the Norwegian coast and has been penetrated by several wells (Figure 2). Below the base rift surface several discrete high-amplitude, Seismic Facies 2 reflection packages occur (Figure 7a). They reach the base rift surface and dip 25–35° to the south offshore the Devonian Hornelen Basin (Figure 6), while showing a series of antiformal and synformal geometries in the Måløy Slope, Uer Terrace, and northern Horda Platform area (Figure 7a). Their geometry is similar to the onshore west plunging folds of the NSDZ [*Chauvet and Séranne*, 1994; *Krabbendam and Dewey*, 1998] and is here interpreted as the offshore extension of the NSDZ (Figure 6). Farther south at around 61°N, another prominent Seismic Facies 2 package dips to the north (LSZ in Figures 7a and 7b). This reflection package, interpreted as the Lomre Shear Zone (LSZ), dips to the north-northwest in the Uer Terrace and to the northwest farther south in the northern Horda Platform area (Lomre Terrace) to 8 s TWT below the area of the Brage Horst (Figure 6). In the hanging wall of the NSDZ and LSZ 10 wells penetrate the basement, of which eight have encountered green micaschists alternating with gneissic rocks rich in quartz and feldspar (Table 2), characteristic of onshore Caledonian nappe units. Furthermore, well 36/7-1 encountered 7 m of gneisses, and well 35/9-3 encountered 13 m of quartzite. Farther north, well 36/1-1 encountered 27 m of augengneiss, possibly representing the offshore extension of the WGR or Middle Allochthon (Figure 6 and Table 2). West of the LSZ and below the Brage Horst another set of high-amplitude west dipping reflections are also locally observed (Figure 7b).

At 61°N and some 30 km west of the Norwegian coast line, a concave band of Seismic Facies 2 reflections show a north dipping northern flank and a south dipping southern flank (BASZ in Figure 7a) underneath

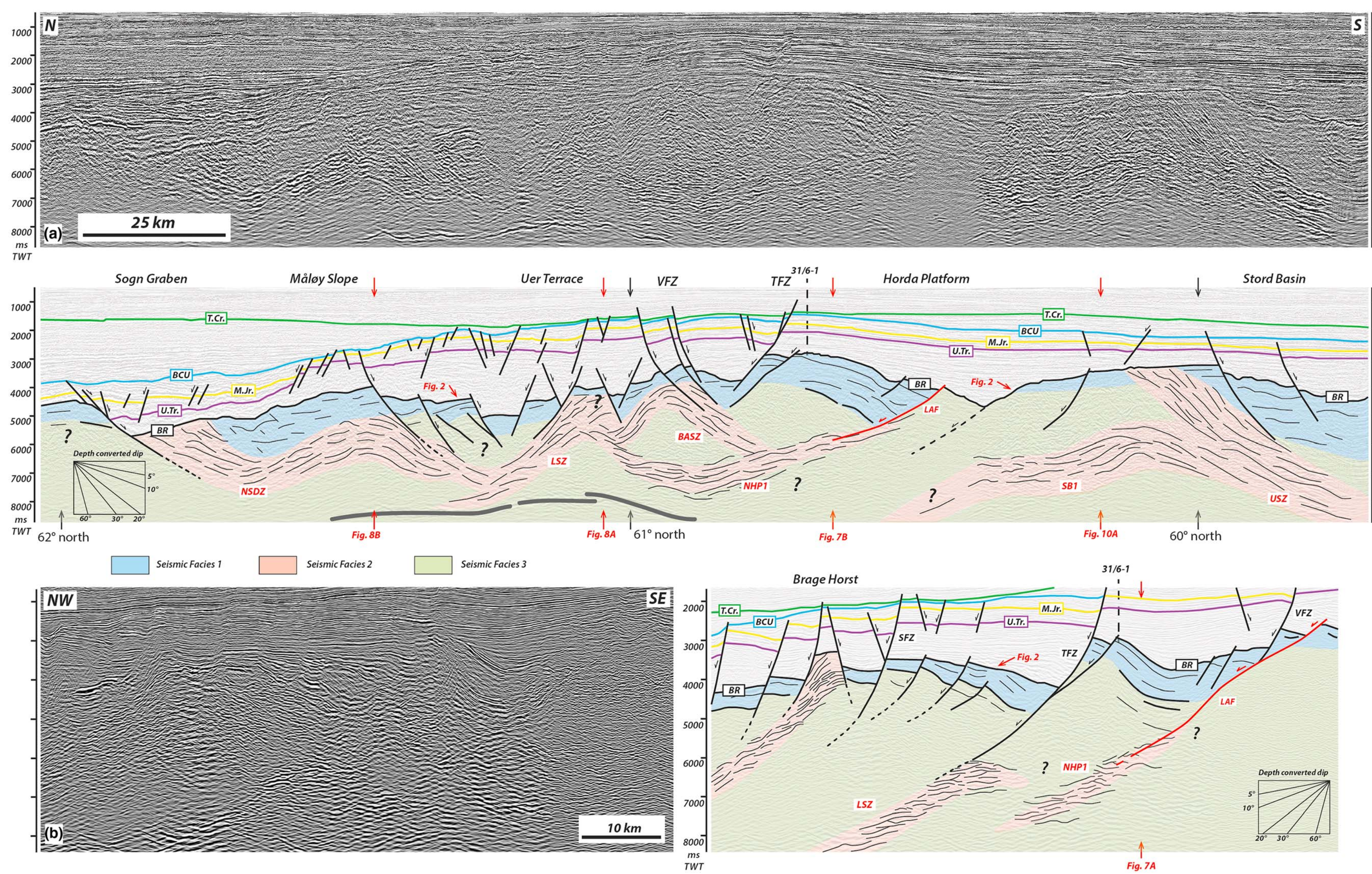

Figure 7. Crustal units and the intrabasement structure in the Måløy Slope and northern Horda Platform area. (a) North-south section across the Måløy Slope and northern Horda Plarform. Several dipping Seismic Facies 2 reflections have been identified below the BR surface. Between 61° and 62°N high-amplitude Seismic Facies 2 reflections are interpreted as offshore extension of Nord-Sogn Detachment Zone (NSDZ) that is folded about west plunging axes similar to its onshore geometry. In the southern edge of cross-section A, two sets of high-amplitude reflections of SF2 are interpreted as the Utsira Shear Zone (USZ) and Stord Basin 1 structure (SB1). (b) Northwest-southeast section showing the Lomre Shear Zone (LSZ) and North Horda Platform (NHP1) structures. Toward the northwest in the hanging wall of the LSZ (northern edge of the Brage Horst) another high-amplitude reflection package has been observed. A true dip indicator (lower right corner) was created for the basement structures, by applying the time-depth relationship obtained from check shots, expanding spread profiles, and ocean bottom seismometer data. T.Cr, Top Cretaceous; BCU, Base Cretaceous Unconformity; M.Jr., Middle Jurassic; U.Tr., Upper Triassic; BR, Base rift surface; ØFS, Øygarden Fault System; VTZ, Vette Fault Zone; TFZ, Tusse Fault Zone; SFZ, Svartalv Fault Zone. See Figure 6 for section locations.

the Vette Fault Zone (VFZ). Farther east, this reflection package can be mapped in the footwall of the Øygarden Fault System (ØFS). The offshore extension of the BASZ dips 30–40° to the south and extends some 40 km to the west where it terminates against the NW dipping LSZ (Figure 6, inset map). It seems possible that this zone of north and south dipping high-amplitude Seismic Facies 2 reflections represents the offshore connection between the Bergen Arc Shear Zone (BASZ) and Nordfjord-Sogn Detachment Zone (NSDZ, Figures 6 and 7a). The two are generally considered to be connected, based on kinematics, strain estimates, and structural mapping [e.g., *Norton*, 1986; *Fossen*, 1992; *Wennberg*, 1996].

The Bergen Arc Shear Zone is connected to the Northern Horda Platform 1 (NHP1) structure beneath the Tusse Fault Zone as part of a major shear zone network (Figure 7). The NHP1 structure is linked to a low-angle (<30°) NW dipping normal fault above 5 s TWT (Figure 7b). This low-angle normal fault strikes NE-SW and offsets the base rift surface. The Vette Fault Zone links vertically to the low-angle normal fault in the north, while about 20 km farther south the low-angle normal fault does not link to any shallower structure (Figures 6, 7a, and 7b). In the northern Horda Platform only two wells have penetrated possible prerift units. Well 32/4-1 drilled some 55 m into granitic conglomerates and sandstones at the crest of the rotated fault block in the footwall of the Vette Fault Zone and well 31/6-1, located 20 km farther east in the footwall of Tusse Fault Zone, encountered about 55 m of quartzitic sandstones underlain by 30 cm of augengneiss (Figure 6 and Table 2).

Above the NSDZ in the Måløy Slope an ~1000 ms thick section of chaotic and low-frequency reflections of Seismic Facies 1 is mapped. Similar packages of reflections can also be observed in the deeper parts of the Uer Terrace above Lomre Shear Zone, in the northern Horda Platform above BASZ and NHP1, and also farther south in the Stord Basin area (Figure 7). These reflections are mainly located between two or more sets of dipping high-amplitude reflections of Seismic Facies 2 and/or in between the base rift surface and an underlying high-amplitude reflection.

5.2. Tampen Spur Area and the East Shetland Basin

On the west side of the northern Viking Graben, crustal structures are characterized by three high-amplitude Seismic Facies 2 reflection packages, including the Tampen (TSZ), Brent (BSZ), and Ninian (NSZ) shear zones (Figure 6, inset map). The Tampen Shear Zone is more than 120 km long, dips 25–35° to the E, and has an arcuate shape in map view (TSZ, Figure 6). In the Marulk Basin, it is crosscut by faults that parallel the NE-SW striking Møre-Trøndelag Fault Complex (Figures 1 and 6). The Brent and Ninian shear zones are concave to the east in map view, dipping to the east in the south and to the southeast in the north, where they link up (BSZ and NSZ, Figure 6). The BSZ is over 100 km in length and dips 15–25° to the east, and the NSZ is about 90 km long, located east of the East Shetland Platform, dips 15–25° to the east but steepens to 20–30° to the south (Figure 6). An important characteristic of these high-amplitude Seismic Facies 2 reflections in the East Shetland Basin is that they laterally transform into narrower (250–500 ms) zones of high-amplitude reflections. However, they still define wider seismic bands than the intrabasement faults described as <30 ms high-amplitude reflections (Figure 4d). East of the Gullfaks area and north of 61°N, the Moho is interpreted at around 10 s TWT based on deep seismic reflection and refraction data [*Christiansson et al.*, 2000; *Odinsen et al.*, 2000] (Figures 6 and 8). In this area high-amplitude reflections of the TSZ offset the Moho and extend downward into the upper mantle (Figure 8). The oppositely dipping LSZ can also be imaged in the lower crust where it terminates against the TSZ at the level of the Moho (Figure 8a).

In the upper parts of the crust the Visund and Inner Snorre faults detach onto the TSZ (Figure 9a). These rift-related faults displace the entire rift fill and are truncated by the Base Cretaceous Unconformity (BCU), while the low-angle normal fault (<30°) only displaces the base rift surface and the lower parts of the rift fill (low-angle fault, LAF, Figure 9a). North of the Gullfaks area, this low-angle normal fault detaches onto the BSZ (Figures 6 and 9a), whereas some 70 km farther south in the East Shetland Basin the steeper fault in the footwall of the Ninian-Hutton Fault detaches onto the BSZ (Figure 9b). Similar spatial relationships between shear zones, low-angle faults, and the steeper faults in the cover have also been observed in the northern Horda Platform.

West of the East Shetland Basin and south of the Tern-Eider Horst, Seismic Facies 2 reflections are interpreted as the Pobie Shear Zone and dip 15°–35° to the west (PSZ, Figures 6 inset map and 9c). *Platt* [1995] shows west dipping high-amplitude reflections in this area and interprets them as Devonian extensional

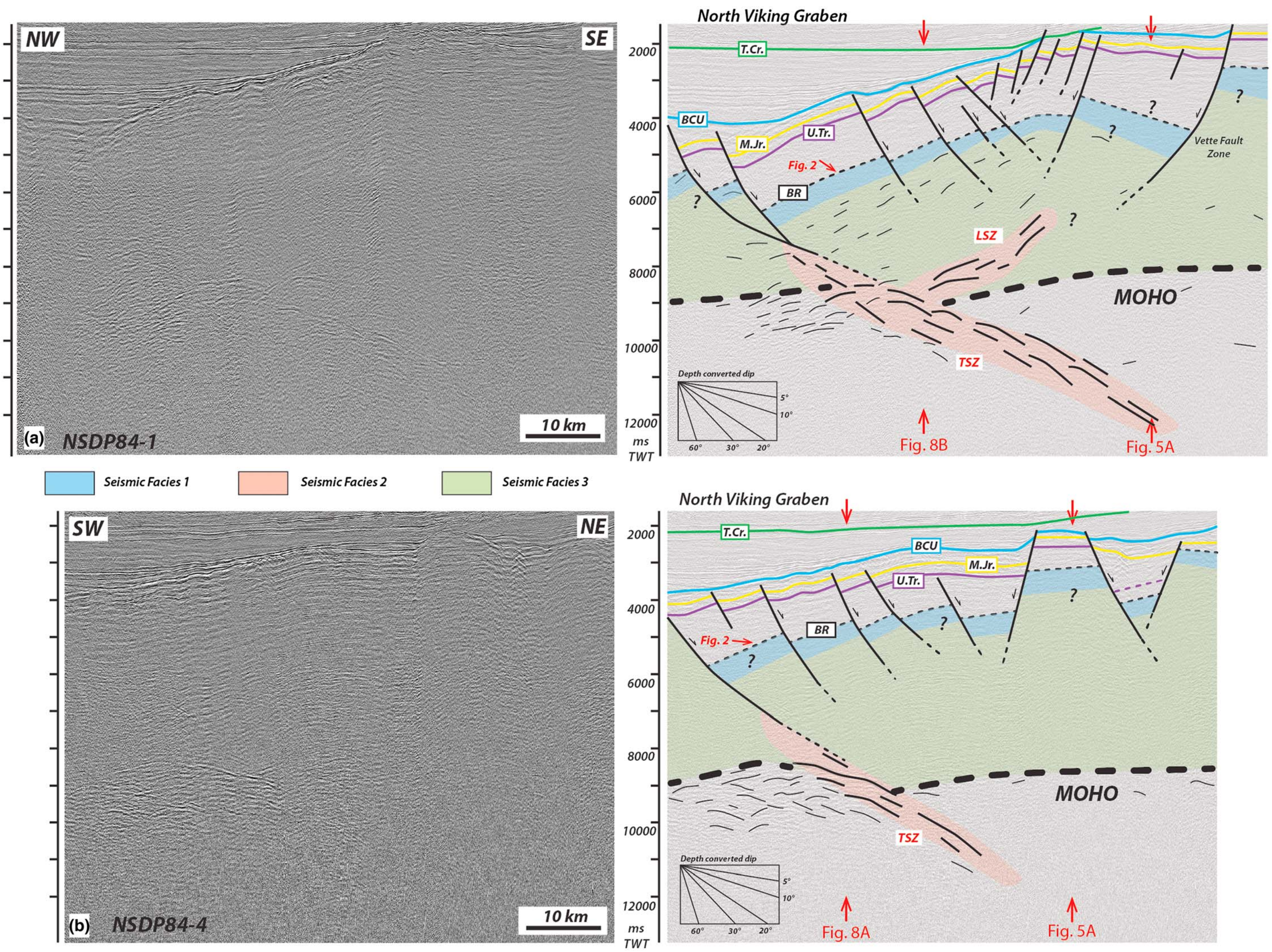

Figure 8. Deep (13 s TWT) seismic reflections showing the high-amplitude Seismic Facies 2 reflections offsetting the Moho in the northern Viking Graben. (a) NSDP84-1 shows the E dipping Tampen Shear Zone (TSZ) extending to the upper part of the mantle. (b) NSDP84-4 strikes subparallel to the Lomre Shear Zone and shows the E dipping TSZ. The interpretation of Seismic Facies 1 reflections is based on the higher-quality intersecting section shown in Figure 7. Interpretation of the Moho is based on *Christiansson et al.* [2000].

reactivation of a possible Caledonian thrust. The PSZ separates east dipping low-amplitude, low-frequency Seismic Facies 1 reflections in its hanging wall from the higher-amplitude and semicontinuous Seismic Facies 3 reflections in its footwall. The Seismic Facies 1 units in the hanging wall of the PSZ are penetrated by well 2/3-1, which drilled metamorphic rocks covered by 37 m of Lower Devonian sandstones (Struie Formation; Figure 9c). These metamorphic rocks are interpreted as a possible remnant of Caledonian nappes in the Pobie Platform, in the northern part of the East Shetland Platform (Table 2 and Figure 9c). The lower boundary of Caledonian nappes in the hanging wall of PSZ is marked by a high-amplitude and east dipping reflection that onlaps onto the PSZ, and this reflection could represent the top of the pre-Caledonian basement (Figure 9c).

5.3. Stord Basin and Utsira High

The Stord Basin occupies a major part of the southern Horda Platform, where it is bounded by the Øygarden Fault system (ØFS) to the east and the Utsira High to the west. This basin is bounded by the northern segment of the Utsira East Fault and an intrabasinal high at 60°N in the north. In the Stord Basin the base rift surface becomes shallower southward, where it is separated from the Ling Depression and Åsta Graben by the Patch

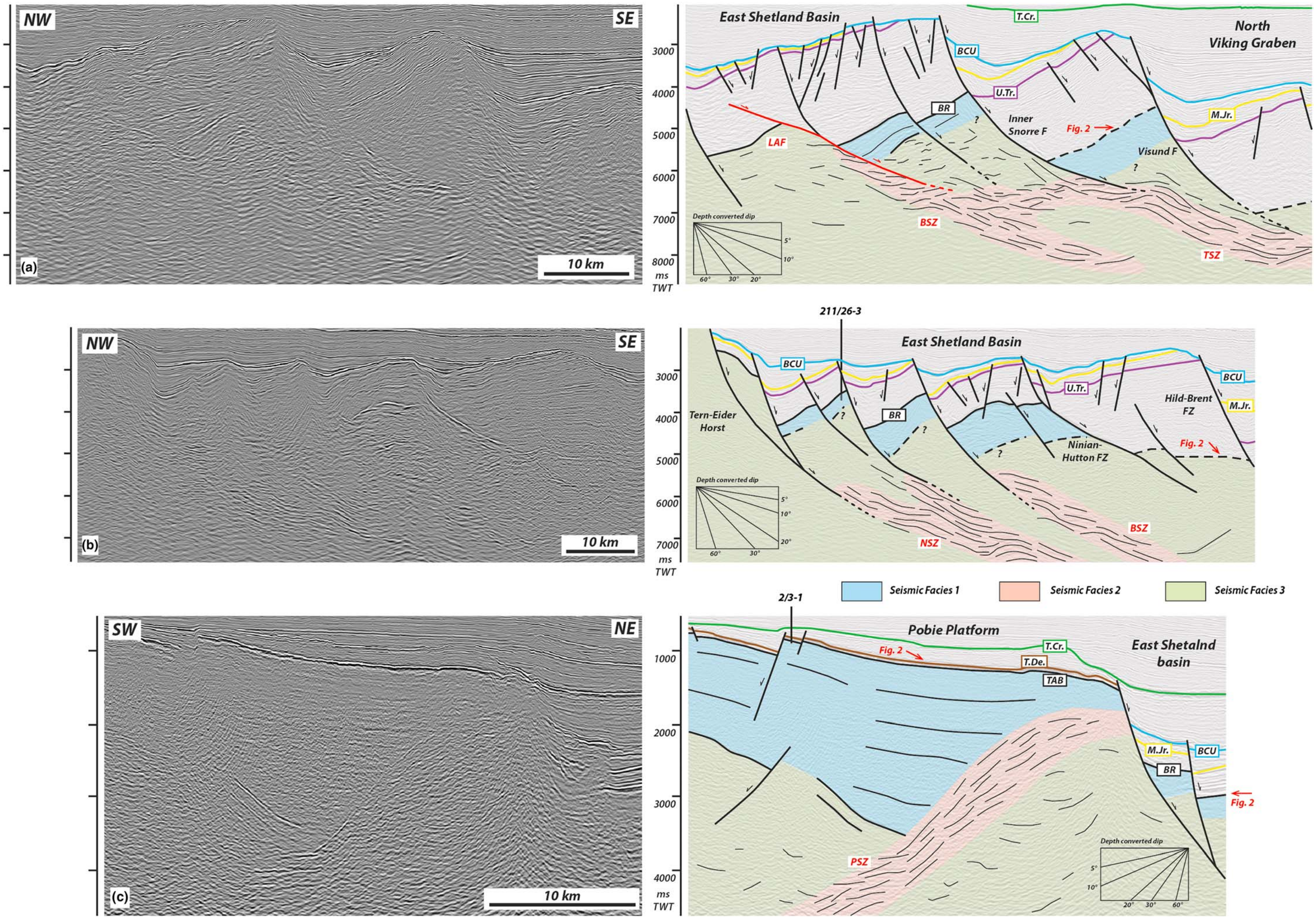

Figure 9. Middle and lower crustal configuration in the Tampen Spur and East Shetland Basin. (a) Tampen and Brent Shear Zones (TSZ and BSZ) located below 6 s TWT and dipping to the east at 15°–25°. The low-angle normal fault (LAF) detaches onto the BSZ and merges with the overlying E dipping fault. (b) NW-SE section showing the Ninian Shear Zone (NSZ) and the southern part of the BSZ. Well 211/26-3 has encountered metasandstones (Devonian?) in this area. (c) The WSW dipping Pobie Shear Zone (PSZ) cut by an E dipping fault in the Pobie Platform (northern edge of East Shetland Platform). In the hanging wall of the PSZ, the upper boundary of Seismic Facies 1 reflections is top acoustic basement surface (TAB) as confirmed by well 2/3-1 which encountered crystalline basement rocks of the Caledonian origin overlaid by 37 m of Devonian sediments. T.Cr.: Top Cretaceous; BCU: Base Cretaceous Unconformity; M.Jr.: Middle Jurassic; U.Tr.: Upper Triassic; T.De.: Top Devonian; BR: Base rift surface.

Bank Ridge (Figure 2). The Stord Basin stores up to 4–5 km of possibly Permian and Triassic sediments [*Steel and Ryseth*, 1990; *Færseth et al.*, 1995], although the chronostratigraphy is not well constrained by well data. The Utsira High separates the Stord Basin in the east from the South Viking Graben in the west. Most of the Utsira High has been an elevated area with subaerial alteration of crystalline basement rocks from the Devonian to the Middle and Upper Triassic, and its highest parts are unconformably overlain by Jurassic sediments [*Slagstad et al.*, 2011; *Riber et al.*, 2015].

In the northern part of the Stord Basin high-amplitude Seismic Facies 2 reflections dip to the south (Utsira Shear Zone, USZ, Figure 7a). A second zone of high-amplitude Seismic Facies 2 reflections underneath the USZ is more shallowly north dipping (Stord Basin 1, SB1, Figure 7a). In the northern part of the Stord basin at 60°N, the geometry of Seismic Facies 2 reflections is very complex with two main south and southeast dipping reflection packages (Stord Basin 2, SB2 and USZ, Figure 10a) separated by a package of Seismic Facies 1 with a synformal and antiformal geometry that links up with the USZ and is displaced by a northwest dipping basement fault at around 6.5 s TWT (SB1, Figure 10a). The folded appearance of the SB1 shear zone is similar to that of the NSDZ in the Måløy Slope area, only at a smaller scale (compare Figures 7a and 10a). This area of

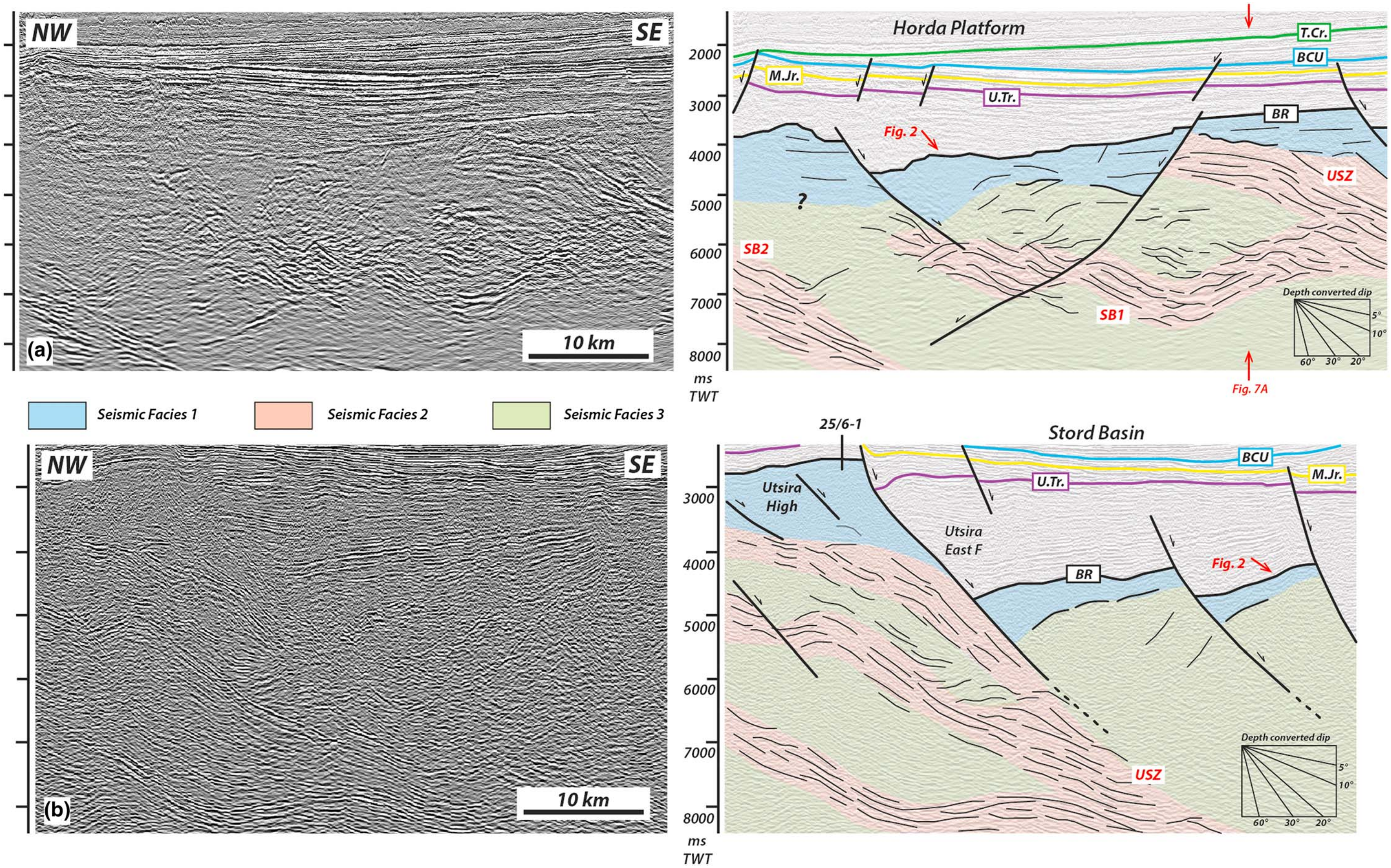

Figure 10. Basement structures in the western and northern margin of Stord Basin. (a) The northern limit of Stord Basin is marked by a complex S and SE dipping Utsira Shear Zone, Stord Basin 2 shear zone (USZ and SB2), and a subhorizontal, but generally NW dipping Stord Basin 1 structure (SB1, see also Figure 7a). (b) The Utsira East Fault detaching onto the USZ in the NW part of the Stord Basin. The Utsira Shear Zone shows three splays in this area and is overlain by the Seismic Facies 1 reflections whose upper part is penetrated by well 25/6-1 and consists of metamorphosed granitic and quartzo-feldspathic gneisses of Caledonian nappe affinity (see Table 2 for rock types and Figure 6 for the well and section location).

complex anastomosing shear zone geometry coincides with the shift in polarity of the rift-related normal faults from west dipping in the eastern part of the Stord Basin to east dipping in the northern part of the Stord Basin and the central segment of the ØFS (Figure 6).

In the northeastern part of the Utsira High, reflections of Seismic Facies 2 are organized vertically into three southeast dipping packages below Seismic Facies 1, separated by medium- to high-amplitude semicontinuous reflections of Seismic Facies 3 (USZ, Figure 10b). The Utsira Shear Zone has a length of more than 150 km, striking mainly NE SW in the north and N-S in the south, where it dips to the east. Along strike, the USZ has a flat-ramp geometry that dips 5–15° in its upper part in the Utsira High, and 15–25° in its deeper parts underneath the Stord Basin (Figure 6). Above the USZ, low-frequency and semicontinuous Seismic Facies 1 reflections have been drilled by well 25/6-1 in the northeastern side of the Utsira High, which encountered 30 m of metamorphosed granitic and quartzo-feldspathic gneiss interpreted as Caledonian nappe units overlain by 300 m of Triassic sediments (Figure 10b). However, the thickness of the Triassic sediments decreases rapidly toward the south in the Utsira High where the basement rocks are overlain by mainly Middle Jurassic sediments (Table 2).

Along the northeastern margin of the Stord Basin at ~60°N, basement seismic reflections are characterized as Seismic Facies 1 (Figure 11a). Seismic Facies 1 units are crosscut by the east dipping faults, including the central segment of the Øygarden Fault System (Figure 11a). Also, in this area we find medium-amplitude and semicontinuous reflections of Seismic Facies 3 with enhanced reflectivity upward (Figure 11a). The favored geologic interpretation of these higher-amplitude reflections is that they could represent the

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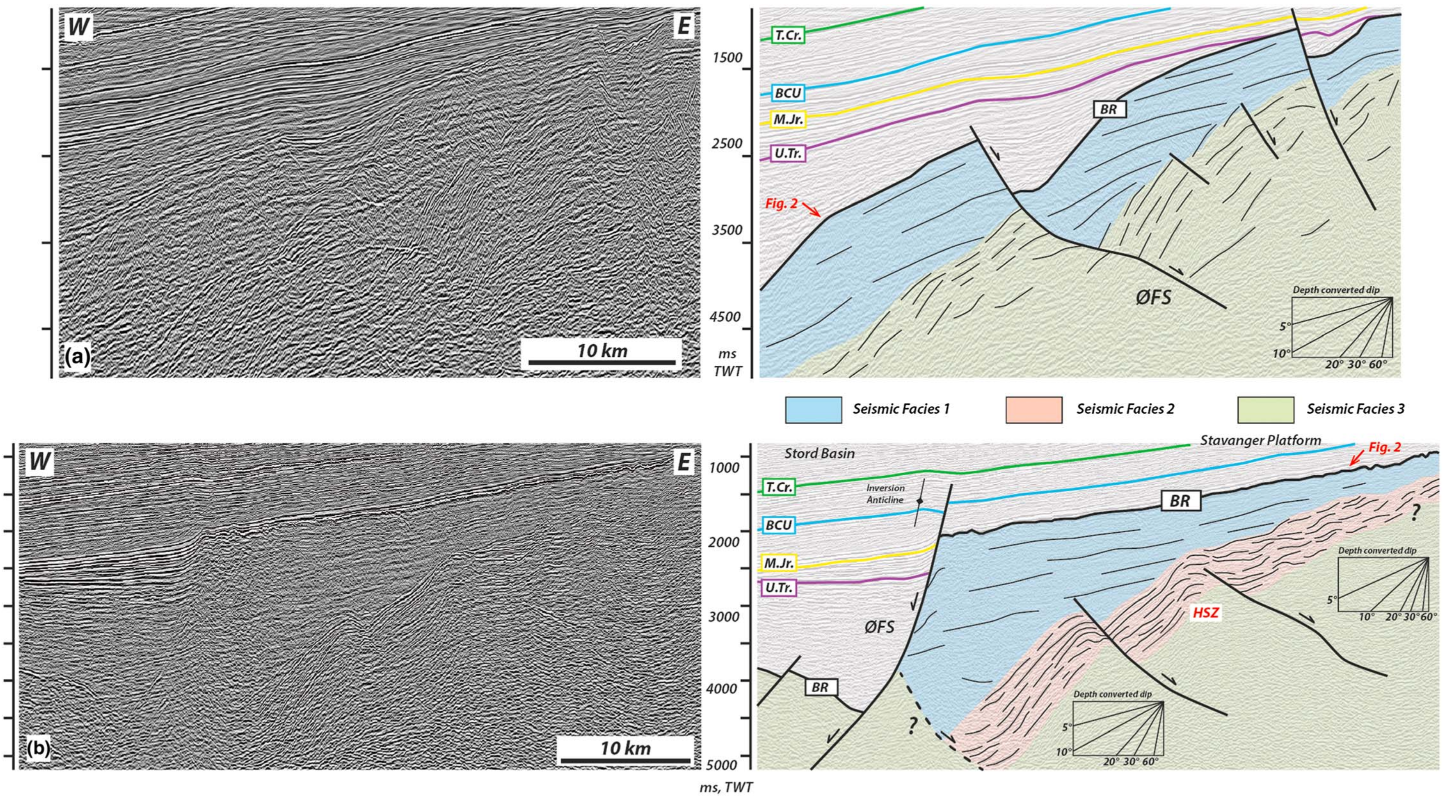

Figure 11. Basement structures in the eastern margin of Stord Basin. (a) At about 60°N the E dipping basement faults, including the Øygarden Fault System (ØFS), offsets the BR surface, and Seismic Facies 1 reflections. (b) Cross-section B shows Seismic Facies 1 reflections bounded by the Hardangerfjord Shear Zone (HSZ) below and the BR surface above. HSZ has a flat-ramp geometry in this area and is displaced by E dipping basement faults. Two dip indicators show true dip in the shallower and deeper parts of the basement.

deformed upper parts of the Proterozoic basement involved in the Caledonian orogeny, i.e., below the Seismic Facies 1 (possible Caledonian allochthon) reflections. Reflections of Seismic Facies 1 are also observed in the footwall of the southern, west dipping segment of the Øygarden Fault System in the Stavanger Platform area at ~59°N (Figure 11b). These Seismic Facies 2 reflections are interpreted as the offshore extension of Hardangerfjord Shear Zone (Figure 6) and appear to be displaced by at least two east dipping basement faults (Figure 11b.)

5.4. East Shetland Platform

In the East Shetland Platform, south of 60°N and west of the Beryl Embayment, two main Seismic Facies 2 reflection packages dip to the west (East Shetland Platform 1 and 2, ESP1 and ESP2, Figure 6 inset map). ESP1 is over 100 km long in the N-S direction and dips 15–25° to the west, and ESP2 is over 150 km long and dips to the west at 15–25° (Figure 12a). The upper tip of ESP2 reaches the base rift surface in the north, where it is displaced by an east dipping normal fault (at 1 s TWT, Figure 12a), but gets deeper toward the south in the Fladen Ground Spur area (Figure 12b). Toward the south, both ESP1 and ESP2 are crosscut by the east dipping faults bounding the Beryl Embayment and the South Viking Graben (Figure 6). In the Witch Ground Graben area, high-amplitude Seismic Facies 2 reflections strike N-S over 60 km in the study area and dip to the east at 15–25° (ESP3, Figure 6). East Shetland Platform 3 shows a ramp-flat-ramp geometry in cross section, and a northeast dipping basin-bounding fault detaches onto the steeper parts of this structure (Figure 12b).

Below the base rift surface, several low-frequency and subparallel east dipping Seismic Facies 1 reflections are penetrated by exploration wells that encountered sediments of Devonian and possibly Carboniferous age. These Seismic Facies 1 reflections onlap onto the ESP1 and ESP2 shear zones (Figure 12a) and form the offshore continuation of the Devonian Orcadian Basin onshore northern Scotland, the Orkneys, and the Shetland Island [*Norton*, 1986; *Platt and Cartwright*, 1998]. *Platt* [1995] and *Platt and Cartwright* [1998]

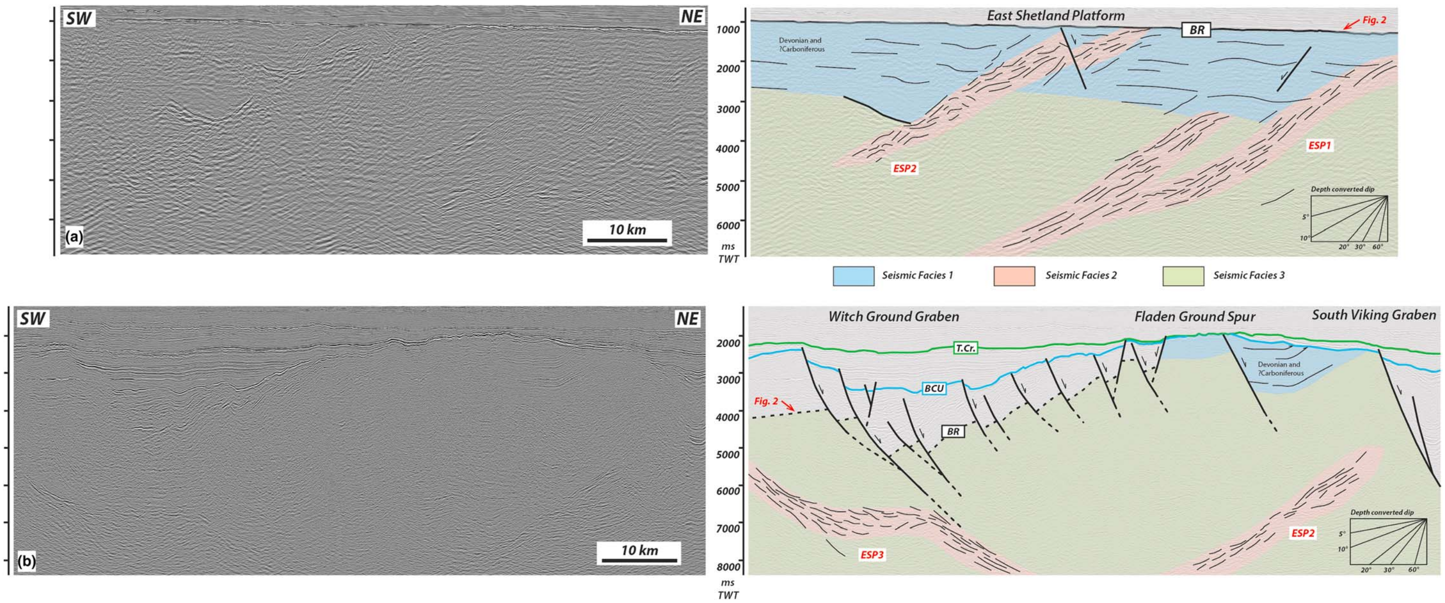

Figure 12. In the East Shetland Platform south of 60°N three Seismic Facies 2 reflection packages were interpreted as East Shetland Platform 1, 2, and 3 (ESP1, 2, and 3). (a) NE-SW cross section showing SW dipping Seismic Facies 2 reflections overlain by Seismic Facies 1 units penetrated by several wells and referred to as Devonian and possibly Carboniferous rocks (Table 2 and Figure 6). (b) The East Shetland Platform 3 structure dipping to the east, showing a ramp-flat-ramp geometry. Rift-related normal faults detach onto the steeper portions of ESP3.

relate these west dipping high-amplitude Seismic Facies 2 reflections to reactivation of Caledonian thrust zones during Devonian extension and the Late Carboniferous-Early Permian Variscan contraction. Farther to the west and southwest, major Devonian structures in northern Scotland and the Shetland Islands have been interpreted as extensional faults, mainly dipping to the east [*Norton et al*., 1987]. In the Fladen Ground Spur above ESP2, a zone of subparallel, high-amplitude, and continuous reflection can be observed in the hanging wall of an east to northeast dipping normal fault. These reflections are comparable with the seismic appearance of Devonian?-Carboniferous structures farther north in the East Shetland Platform. Devonian and Carboniferous structures are also probably present in the deeper parts of the Witch Ground Graben and Outer Moray Firth in the southwestern margin of the study area [*Mcquillin et al*., 1982; *Harker et al*., 1987; *Rogers et al*., 1989; *Patruno and Reid*, 2017].

5.5. Åsta Graben and Sele High

At around 59°N in the footwall of the Øygarden Fault System two packages of oppositely dipping Seismic Facies 2 reflections occur, separated by a basement high at the location of well 17/3-1 (Figure 13a). The north dipping Seismic Facies 2 reflections are interpreted as the Hardangerfjord Shear Zone and the south dipping high-amplitude reflections are interpreted as the Åsta Shear Zone (ÅSZ) that has a concave to the southwest map view geometry, with over 100 km length and 20–30° dip. In this area the Øygarden Fault System detaches onto the HSZ, bounding the Stord Basin to the south. The intrabasinal high defined by these two shear zones (HSZ and ÅSZ) separates the Stord Basin from the Åsta Graben, and the shallow basement encountered in well 17/3-1 (at ~2500 ms TWT, 2811 m) involves gray metamorphic rocks of greenschist facies of which the uppermost 7–8 m are weathered and overlain by the Triassic Smith Bank Formation (Table 2).

In the southern part of the Åsta Graben and the Stavanger Platform two main packages of Seismic Facies 2 reflections are interpreted as the offshore extension of the Karmøy and Stavanger shear zones (Figures 6 and 13b). The offshore part of the Karmøy Shear Zone (KSZ) is over 150 km long, dips 15–30° to the northwest, and is displaced by the east dipping Sele East Fault System (Figure 13b). In the north, the KSZ links up with the Åsta Shear Zone, and in the south, Seismic Facies 2 reflections in the footwall of the KSZ are interpreted as a splay of this structure dipping to the west at 10–25° (Flekkefjord Shear Zone, FSZ, Figures 6 and 13b) [*Phillips et al*., 2016]. The offshore part of the Stavanger Shear Zone is

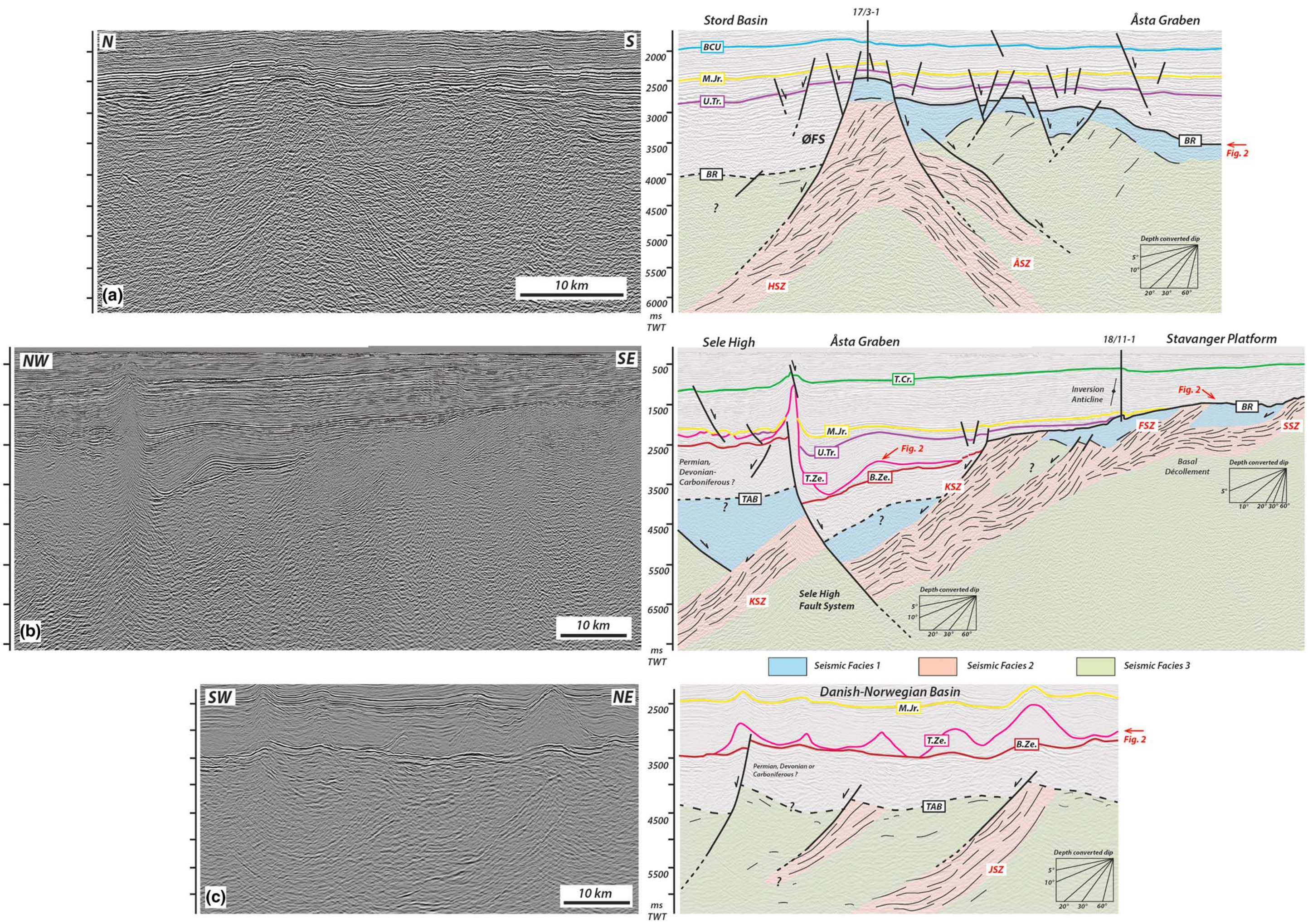

Figure 13. Basement structures in the Åsta Graben and Sele High area. (a) The Hardangerfjord Shear Zone (HSZ) dipping to the north and the Åsta Shear Zone (ÅSZ) dipping to the south. (b) Series of NW dipping high-amplitude Seismic Facies 2 reflections in the Stavanger Platform. The Karmøy Shear Zone (KSZ) is displaced by the Sele High Fault System in this area. Two true dip indicators show the westward steepening of KSZ. Well 18/11-1 drilled quartzite and chloritic schist above Seismic Facies 2 reflections, interpreted as Caledonian nappes units. (c) SW dipping Seismic Facies 2 reflections in the northern Danish-Norwegian Basin (Jæren Shear Zone, JSZ). Sandstones present under the Base Zechstein evaporites have been referred to as the remnant of possible Devonian and Carboniferous sediments in the Sele High and the north of Danish-Norwegian Basin. Top Zechstein: T.Ze. Base Zechstein: B.Ze, and Top Acoustic Basement TAB.

over 100 km long and dips to the west at $<30°$. The Stavanger and Flekkefjord shear zones merge at around 2.5 s TWT, possibly reactivating the basal Caledonian décollement, and link up with the Karmøy Shear Zone, together forming a wider zone of high-amplitude reflections in this area (Figure 13b). This area has previously been explored by means of the coast-parallel ILP lines [*Klemperer and Hurich*, 1990; *Færseth et al.*, 1995; *Gabrielsen et al.*, 2015; *Fossen et al.*, 2016] by which the offshore extension of major west and northwest dipping onshore shear zones, namely, the Hardangerfjord, Karmøy, and Stavanger Shear Zones (Figure 6), was demonstrated.

Seismic Facies 1 reflections above the SSZ and KSZ in the Stavanger Platform were drilled by well 18/11-1 and exhibits gray and green quartzo-feldspathic and chloritic schist interpreted as Caledonian nappe units. High-amplitude Seismic Facies 2 reflections are mapped below the Permian Zechstein evaporites west and southwest of the Sele High in the northern part of the Norwegian-Danish Basin (Jæren Shear Zone, JSZ, Figure 13c). The Jæren Shear Zone strikes over 100 km and dips 20–30° to the west-southwest underneath subparallel and subhorizontal reflections. These reflections are located below upper Permian Zechstein evaporites and are interpreted as Lower-Middle Permian, Carboniferous or Devonian sediments [*Heeremans and Faleide*, 2004].

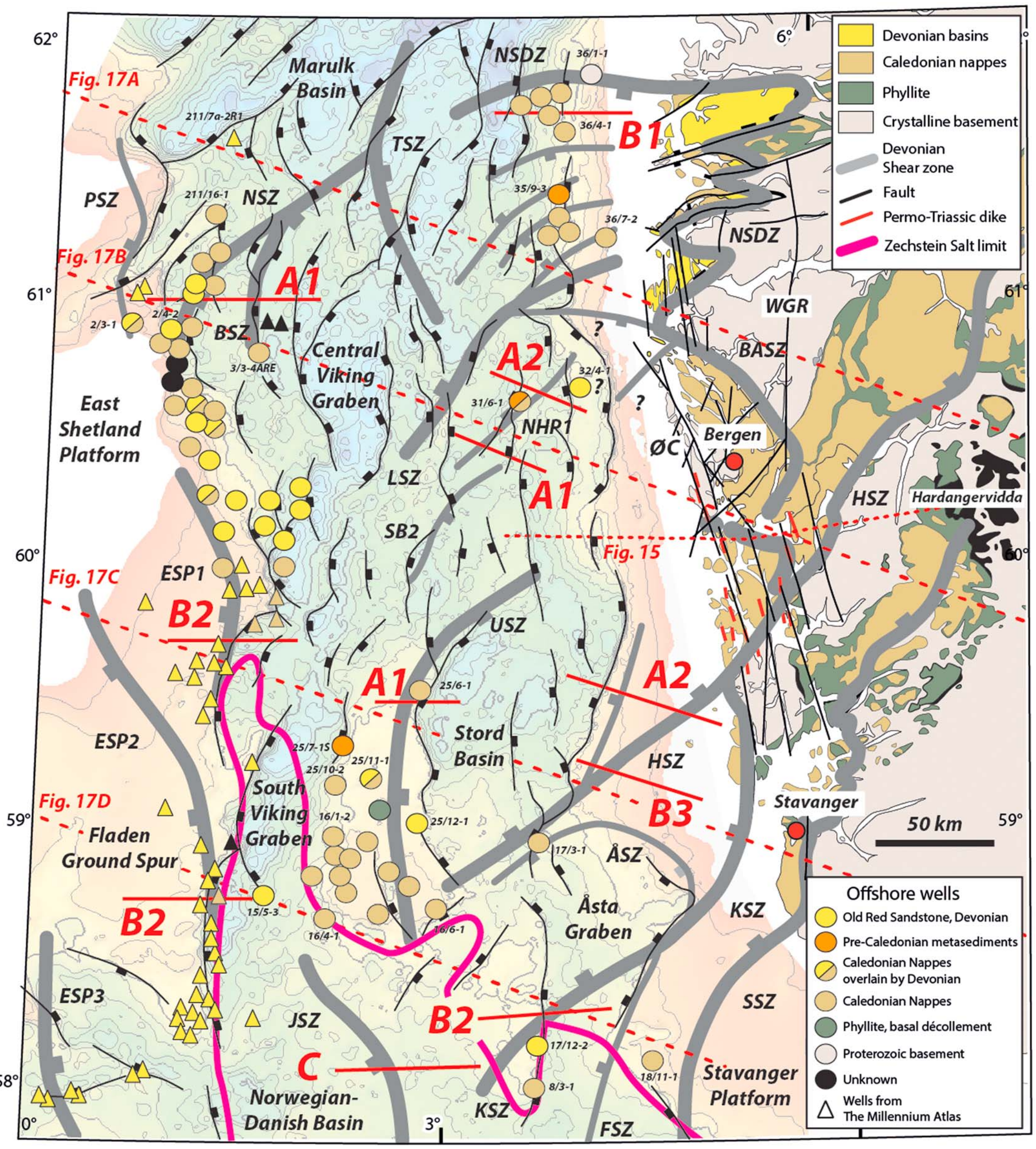

Figure 14. Onshore-offshore relationship and the distribution of offshore prerift structures and rock units based on well information. Prerifting rocks are divided into five main units comprising the following: (1) Proterozoic crystalline rocks in beige, (2) Pre-Caledonian metasediments in orange, (3) Phyllites (basal decollement) in dark green, (4) Caledonian nappe units in brown, and (5) Devonian sandstones and conglomerates in yellow. Circles show the basement wells used in this study, and triangles are basement wells from The Millennium Atlas [*Bassett*, 2003; *Marshall and Hewett*, 2003].

6. Prerift Rock Types in Southwest Norway and the Northern North Sea

The onshore bedrock prerift geology of SW Norway can be subdivided into four main units: (a) Baltica Proterozoic basement, (b) the basal décollement zone, (c) Caledonian orogenic wedge, and (d) very low grade Devonian conglomerates and sandstones. The Proterozoic basement was subjected to westward increasing Caledonian deformation and metamorphism northwest of the HSZ in the region known as the Western Gneiss Region (WRG) and the Øygarden Complex, north and west of Bergen, respectively [*Andersen and Jamtveit*, 1990; *Fossen*, 1992; *Fossen and Hurich*, 2005] (Figure 2). The basal décollement zone overlays the Baltica basement and includes a continuous zone of phyllites, overlain by remnants of the Caledonian orogenic wedge (nappe units). The latter are particularly well preserved in the hanging walls of major Devonian extensional shear zones. Devonian conglomerates and sandstones resting unconformably on top

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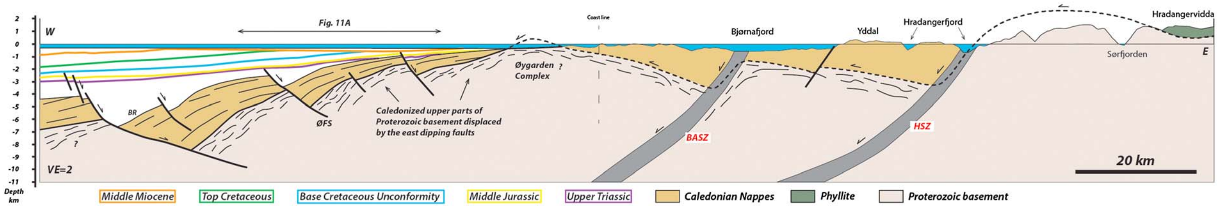

Figure 15. East-west cross section showing the onshore-offshore relationships between Caledonian nappe units, Devonian shear zones, and Proterozoic crystalline basement at 60°N. BR, base rift surface; ØFS, Øygarden Fault System.

of the outboard nappe units are found in the hanging wall of the NSDZ only (Figure 2). Prerift rock units encountered by 72 deep wells in the northern North Sea can be grouped into (a) banded gneisses and augengneiss, (b) alternating green micaschist, gneiss and granite, (c) quartzite and metasandstone, and (d) Devonian sandstones and conglomerates (Figure 14). The majority of these basement wells penetrate only a few meters or tens of meters into the prerift rocks; all (excluding 36/1-1) in the subhorizontal, low-frequency, and low-amplitude reflections of Seismic Facies 1. It is therefore not possible, based on seismic facies alone, to unequivocally map and distinguish between different types of lithologic units offshore.

Basement wells confirmed Seismic Facies 1 to be Caledonian nappes in the east margin of the Viking Graben (brown circles in Figure 14). In the western margin of the Viking Graben, Caledonian nappes appear to be overlain by Devonian (meta)conglomerates and sandstones (Figure 14). Devonian units also show low-amplitude and low-frequency seismic facies. Prerift units in the East Shetland Basin and Platform change from nappe-dominated units in the north to Devonian "Old Red Sandstones" toward the south. Devonian units in the southern parts of the East Shetland Platform have been considered as the northwestern part of the Orcadian Basin [*Coward*, 1990; *Wilson et al.*, 2010]. Along the eastern margin of the Viking Graben, metasandstones, quartzite, and conglomerates have been drilled, showing low-amplitude and low-frequency Seismic Facies 1 reflections. Quartzite and metasandstones encountered in the northern Horda Platform (well 31/6-1) are interpreted as Proterozoic metasediments, metamorphosed during the Caledonian orogeny (orange circles in Figure 14) [*Slagstad et al.*, 2011]. In the northern Horda Platform about 40 km southwest of the Devonian Solund Basin, well 32/4-1 drilled 54 m into granitic conglomerates with a pale red sandy matrix (Figure 14). These units have not been dated; hence, they could represent Devonian or Permian rocks below lower Triassic units. Rock units observed in well 32/4-1 show seismic facies similar to those produced by the red and brown Devonian sandstones and conglomerates drilled in many wells in the East Shetland Platform (Table 2 and Figure 14). However, red and unmetamorphosed conglomerates drilled in the northern Horda Platform and Utsira High are different from the greenish and gently metamorphosed Devonian rocks onshore West Norway.

Mesoproterozoic augengneisses in well 36/1-1, some 30 km offshore the Hornelen Basin are linked to Seismic Facies 3 and have previously been related to the Western Gneiss Region (Proterozoic basement) [*Slagstad and Davidsen*, 2007; *Nordgulen and Andresen*, 2008]. Offshore extension of the WGR and southward changes to the mainly Caledonian nappe units in this area have also been previously interpreted from magnetic modeling [*Smethurst*, 2000]. This adds support to our interpretation of an offshore extension of NSDZ, toward the Sogn Graben, based on the seismic facies descriptions. The spatial relationship between Proterozoic basement, Caledonian nappes, Devonian extensional shear zones, and rift-related normal faults is shown in the east-west cross section from the onshore Hardangervidda area to the footwall of the east dipping segment of Øygarden Fault System (Figure 15).

7. Discussion

We have described the seismic expressions of prerift basement units in the northern North Sea, and by integrating seismic and well data, we have attempted to interpret the basement seismic facies in terms of known onshore geologic units. We have identified one of the seismic facies (Seismic Facies 2) as major basement shear zones that are interpreted to be both reactivated and nonreactivated Devonian extensional shear zones. Here we discuss further the nature and the significance of basement seismic facies, the distribution and geometry of prerift basement units and structures, and the influence of these structures on the location and the geometry of the rift-related faults and depocenters.

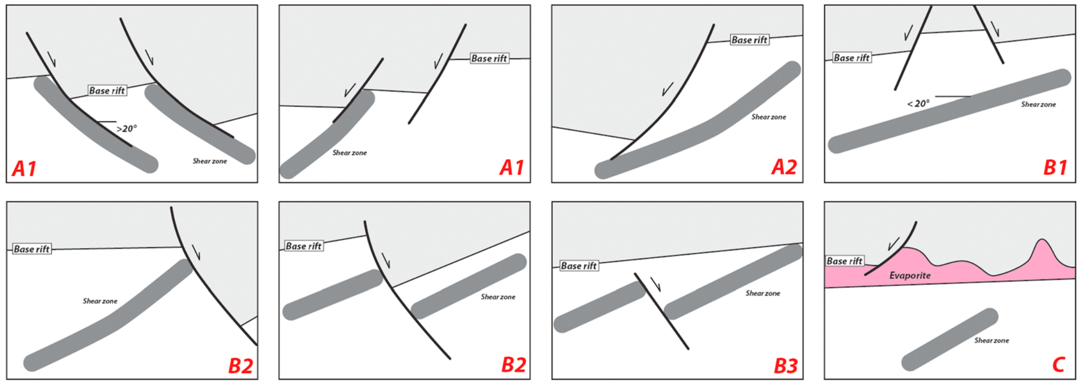

Figure 16. Cartoons summarizing types of basement shear zones and fault interaction observed in the study area. Type A1 is where the entire shear zone is reactivated, and type A2 is when only a portion of the shear zone in reactivated. In type A1 interaction the shear zone localizes the strain and controls the location and geometry of rift bounding faults. Type B1 is when the shear zone is neither reactivated nor crosscut by rift-related faults. This type is observed offshore Devonian Hornelen Basin where the shear zone dips <20°. Type B2 is where shear zones are crosscut by rift-related faults regardless of their orientation relative to the extension direction. Type B3 is the case where the shear zone is displaced by a basement fault prior to the onset of rifting. Type C is where the shear zone is not reactivated due to the presence of mechanically weak units (here evaporites) at the base of the rift succession. See Figure 14 for examples from the study area.

7.1. Geometry, Distribution, and Seismic Character of Seismic Facies 2 (Basement Shear Zones)

Seismic Facies 2 reflections are strong and continuous, dipping 5–40° and interpreted as mylonitic shear zones. In general, the structures defined by the Seismic Facies 2 are mainly N-S or NE-SW trending, with additional NW-SE trending (e.g., ESP2 and JSZ) and E-W trending (e.g., NSDZ) populations (Figure 14). These orientations are identical to those of onshore Devonian extensional shear zones, with which some zones of Seismic Facies 2 can be linked (e.g., Hardangerfjord, Karmøy, and Stavanger shear zones) [*Færseth et al.*, 1995; *Gabrielsen et al.*, 1995; *Hurich*, 1996]. In addition, *Smethurst* [2000] presents gravity and magnetic maps showing NW-SE trending lineaments in the northern Horda Platform and Måløy Slope. However, we have not been able to identify this trend in the available seismic data set.

The distribution of Seismic Facies 2 structures indicates that Devonian extensional shear zones exist under the northern North Sea rift basin, including the Horda and East Shetland Platforms, East Shetland Basin, and the Viking and Sogn Grabens (Figure 6). This adds to the Devonian, postorogenic, extensional strains recorded onshore. The thickness of the offshore shear zones is typically several kilometers, implying at least ten and probably several tens of kilometers of offset (see discussion in *Fossen and Hurich* [2005]). Furthermore, whereas most onshore Norway extensional shear zones of this type dip toward the west or northwest, i.e., toward the Caledonian hinterland, the shear zones mapped offshore also dip to the east and southeast (e.g., NSDZ, BASZ, and USZ in Figure 14). In the east Greenland Caledonides and offshore parts of the Scottish Caledonides, Devonian postorogenic extension structures dip to the east (toward the hinterland) [*Andresen et al.*, 2007; *Gilotti and McClelland*, 2008; *Wilson et al.*, 2010; *Bird et al.*, 2015]. The presence of east, west, and south dipping shear zones in the northern North Sea area indicates that postorogenic extensional structures developed in various directions in the central (hinterland) parts of the Caledonides, while hinterland dipping structures dominate the flanks of the orogenic belt.

7.2. Role of Basement Shear Zones During Rifting

Basement shear zones are likely to respond to rifting subject to their orientation (strike and dip) relative to the extension direction and their mechanical/rheological properties [*Daly et al.*, 1989; *Fraser and Gawthorpe*, 1990; *Ring*, 1994; *Færseth*, 1996; *Morley et al.*, 2004; *Bellahsen et al.*, 2013]. In the Horda Platform (Stord Basin) and across the Viking Graben in the East Shetland Basin, prerift structures mainly strike NE-SW and N-S, oblique or perpendicular to the proposed E-W Permo-Triassic extension direction [*Badley et al.*, 1988; *Gabrielsen et al.*, 1990; *Ziegler*, 1990; *Færseth*, 1996] (Figure 14). In these areas, especially in the Stord Basin, a thick (>4 km) Permo-Triassic succession is preserved above the base rift surface (Figures 7, 9, and 10).

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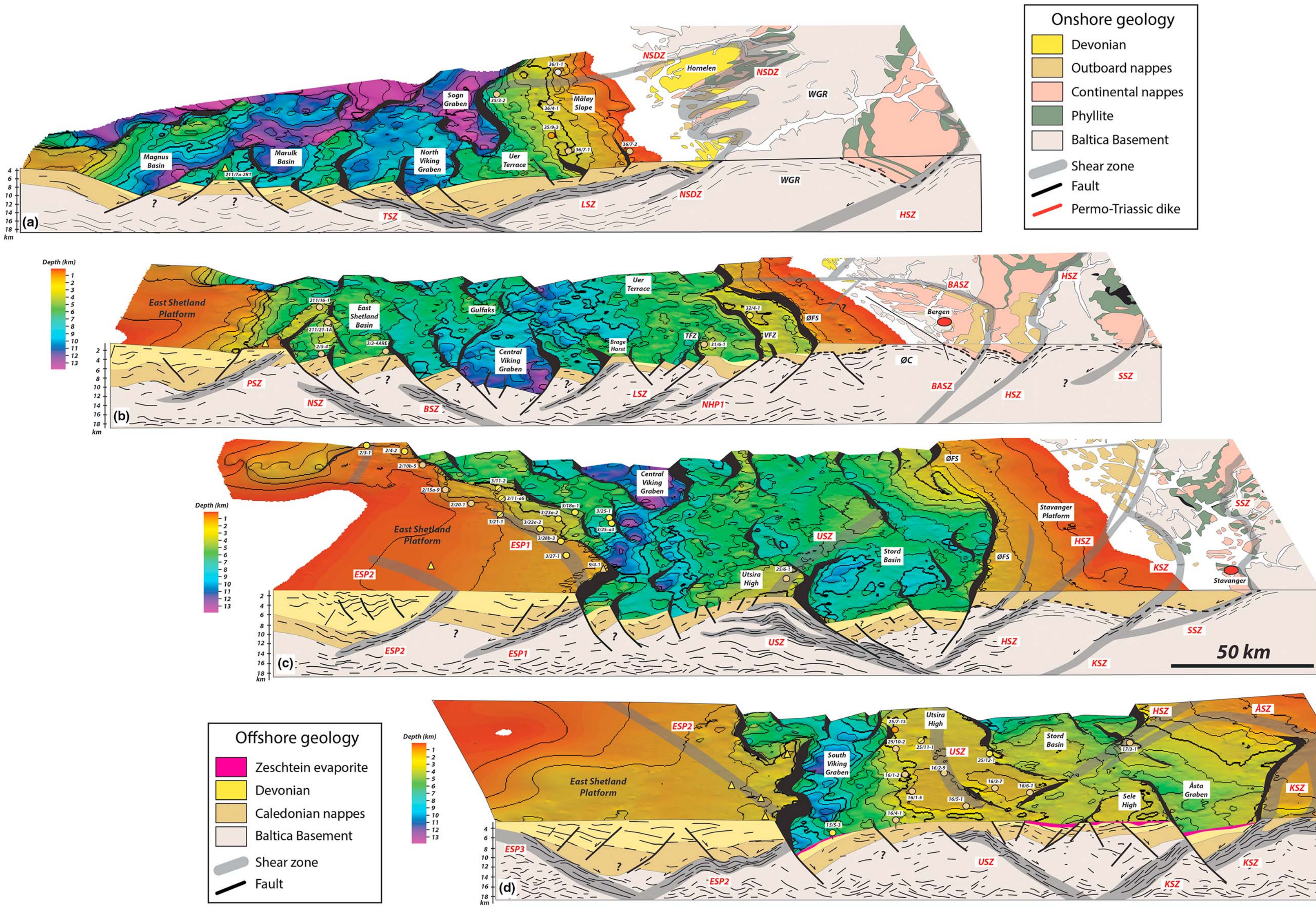

Figure 17. Three-dimensional view of the northern North Sea rift and southwestern Norway showing the offshore extension of onshore Devonian shear zones below the base rift surface and their relationship to the rift-related major faults. (a) The relationship between NSDZ, LSZ, and TSZ in the Måløy Slope and north Viking Graben area. LSZ has flat-ramp geometry and terminates against the oppositely dipping and steeper TSZ below the north Viking Graben. (b) Intrabasement structures across the northern Horda Platform, central Viking Graben, and East Shetland Basin. (c) Relationship between the W dipping SSZ, KSZ, and HSZ and the E dipping USZ across the Stord Basin. (d) Section across the Åsta Graben, Sele High, Utsira High, and southern part of the East Shetland Platform. Note that the subdivision of Caledonian nappes has not been carried out offshore.

The NE-SW and N-S striking shear zones in the Horda Platform and East Shetland Basin were more favorably oriented for reactivation with respect to the E-W Permo-Triassic extension direction and therefore acted as a control on the location and geometry of Permo-Triassic major normal faults and rift depocenters (e.g., Stord Basin and East Shetland Basin, A1 and A2 in Figure 16, see also Figure 14 in *Phillips et al.* [2016]). In contrast, on the Måløy Slope, north of 61°N, most prerift structures strike E-W to ENE-WSW, i.e., close to the Permo-Triassic extension direction and were less likely to be reactivated (B1 in Figures 16 and 17a). This could explain the lack of Permian and Triassic depocenters in this area. Not all favorably oriented prerift structures reactivated during rifting. For instances in the East Shetland Platform, the mainly west dipping PSZ and ESP2 did not reactivate and were instead crosscut by oppositely dipping normal faults (B2 in Figures 16, 17b, and 17c, see also Figure 14 in Phillips *et al.* [2016]). Such overprinting relationships are also documented in the Åsta Graben, where the E dipping Sele High fault system offsets the NW dipping KSZ (B2 in Figures 16, 12, and 17d).

In the northern Utsira High and Stavanger Platform, the USZ and HSZ steepen with depth from <10° to 25–30°, and only the steeper parts of these shear zones seem to be reactivated and hard linked to the rift-related normal faults in the cover (Figures 10b and 11b). However, it is difficult to conclude if a fault connected to a shear zone at depth nucleated on the shear zone and propagated upward, or initiated in the rift fill and propagated downward to link with the underlying shear zone [*Baudon and Cartwright*, 2008]. In the southern Stavanger Platform the shallowly (<5°) dipping SSZ and the basal Caledonian décollement do not show evidence of reactivation (Figure 13b). Similarly, no major rift-related faults developed above LSZ (10°–15°) in the Uer Terrace, in contrast to the higher-angle (25°–35°) TSZ in the Tampen Spur area, where major east dipping normal faults are rooted in the TSZ (A1 in Figures 16 and 17a). These observations suggest that shear zones dipping less than 15° (present dip) were not reactivated. Numerical modeling has shown that preexisting structures can be reactivated at 20° due to plastic compaction reducing the effective friction [*Lecomte et al.*, 2012]. The difference between our observation and numerical models can be accounted for by the block rotation and the basin subsidence during the subsequent synrift and postrift evolution [*Bell et al.*, 2014].

Another feature of the study area is the presence of shear zones below the Upper Permian Zechstein evaporites and Lower Permian Rotliegend clastics in the northern Danish-Norwegian Basin (JSZ Figure 13c). In this area no major rift-related faults offset the base rift surface (Figure 2). In the northern Danish-Norwegian Basin the presence of Permian evaporites decouples reactivated basement structures from rift-related normal faults above the evaporites [*Heeremans and Faleide*, 2004]. Hence, the suprasalt fault and basin geometry are controlled by the (re)distribution of evaporites [*Duffy et al.*, 2013; *Ge et al.*, 2016], regardless of the reactivation of preexisting basement shear zones (here JSZ) at depth (C in Figure 16).

7.3. Tectonic Affinity of Basement Rocks in the Northern North Sea Rift

The scarcity of basement wells drilled into the crystalline basement and the difficulties involved in separating different rock units or terranes from interpretation of seismic reflection data alone makes it difficult to predict how far the Baltican and Laurentian cratons extend into the northern North Sea, and therefore, the location, width, and nature of the Iapetus suture zone. However, it is clear from onshore Caledonian basement pressure-temperature data that the suture zone must be located not too far offshore in the northern part of the study area, probably in the Sogn-Viking Graben area [*Fossen et al.*, 2016]. Gravity and magnetic modeling across the northern Horda Platform and the East Shetland Basin may potentially add to such an interpretation, and a tentative interpretation was presented by *Fichler et al.* [2011], who interpreted the basement underneath the East Shetland Basin to consist entirely of island arc rocks, and the Horda Platform to consist entirely of metasediments. While island arc complexes are to be expected in the hinterland or the suture zone, 15–20 km of metasediments under the Horda Platform [*Fichler et al.*, 2011] is unrealistic and not supported by onshore geology. Hence, to address the nature of basement in terms of tectonic affinity, future work should take into account basement seismic facies interpretation as developed in this paper, together with better gravity and magnetic data.

8. Conclusions

An extensive data set of 2-D seismic reflection data together with well information has been used to study the prerift rock units and the distribution and the geometry of the intrabasement structures in the northern North Sea rift. Three seismic facies have been identified, interpreted to largely represent layered Caledonian nappes and overlying Devonian (meta)sediments (Seismic Facies 1), ductile shear zones (Seismic Facies 2), and a facies that largely represent Proterozoic basement, at least east of the Viking/Sogn Graben (Seismic Facies 3). However, it is difficult to distinguish between Caledonian nappes and Devonian (meta)sediments based on seismic expression alone.

Close to the Norwegian mainland, Seismic Facies 2 reflections that we interpret as ductile shear zones can be linked with onshore Devonian extensional shear zones. This indicates that the style of Devonian extension known onshore West Norway continues across the northern North Sea. The offshore population contains E to SE dipping shear zones, as opposed to only W-NW dipping shear zones onshore. The offshore shear zones extend to the lower crust and dip $<40°$ to the NW and S in the Måløy Slope, E-SE and W-NW in the Horda Platform, E in the East Shetland Basin, and E and W-SW in the East Shetland Platform. Our interpretation implies that Devonian strain and ductile extension is distributed across a wide portion of the Caledonian orogenic belt, from central South Norway to the Shetland Platform, and that the extension and tectonic crustal thinning following the Caledonian convergence between Laurentia and Baltica was significantly larger than that recorded by onshore structures alone.

Our base rift (Permo-Triassic rift) time-structure map reveals a composite fault pattern that is the combined effect of the two rift phases on basement. Some of the major rift faults are controlled by basement shear zones, but only shear zones with present-day dips higher than ~15° were reactivated. Reactivation of basement shear zones was more widespread at early stages of the rift history, before these structures rotated to lower dips less favorable for reactivation. Furthermore, several basement shear zones have been offset by rift-related faults regardless of their orientation relative to the ~E-W extension direction.

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