Influence of basement in structuring of the North Sea basin, offshore southwest Norway

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The coast-parallel deep reflection profile ILP-10, located ca. 50 km west of the Norwegian coastline, suggests that major geological Precambrian and Caledonian units well known from the west Norway mainland can be correlated to similar basement units in the shelf area. The offshore continuation of the Nordfjord–Sogn detachment and the Hardangerfjord shear zone related to Devonian extension, bound two N- and NW-facing half-grabens containing lower Palaeozoic rocks of the Caledonian Allochthon. The basement units constitute the substrate for Permo-Triassic sediments within the bulk of the study area. Following mid-Permian–early Triassic (ca. 260–240 Ma) stretching, crystalline basement thickness on the Horda Platform was, in places, reduced to some 12–13 km, and the basement rocks are now covered by 8–10 km sediments. The block-bounding and extensional basement-involved master faults of this generation have a spacing of 15–20 km. Permo-Triassic faulting resulted in throws of up to 4–5 km, whereas throws related to the Jurassic–early Cretaceous reactivation are negligible (< 300 m). The Permo-Triassic master faults in the study area are discordant to structural trends in the coastal area which result from Caledonian compression and Devonian extension. It is suggested that both the orientation and spacing of the master faults were influenced by a Precambrian N–S structural grain, whereas changes in fault polarity and associated accommodation zones are related to basement grains represented by the Bergen Arcs of Caledonian origin and the Nordfjord–Sogn detachment representing a Devonian shear zone. While the Jurassic extension in the northern North Sea was fairly localized and concentrated to the Viking Graben, the Permo-Triassic extension was distributed across the total width of the basin. However, the most pronounced Permo-Triassic fault activity was concentrated to the eastern part of the northern North Sea basin and it is proposed that the Permo-Triassic rift axis was situated on the present Horda Platform.

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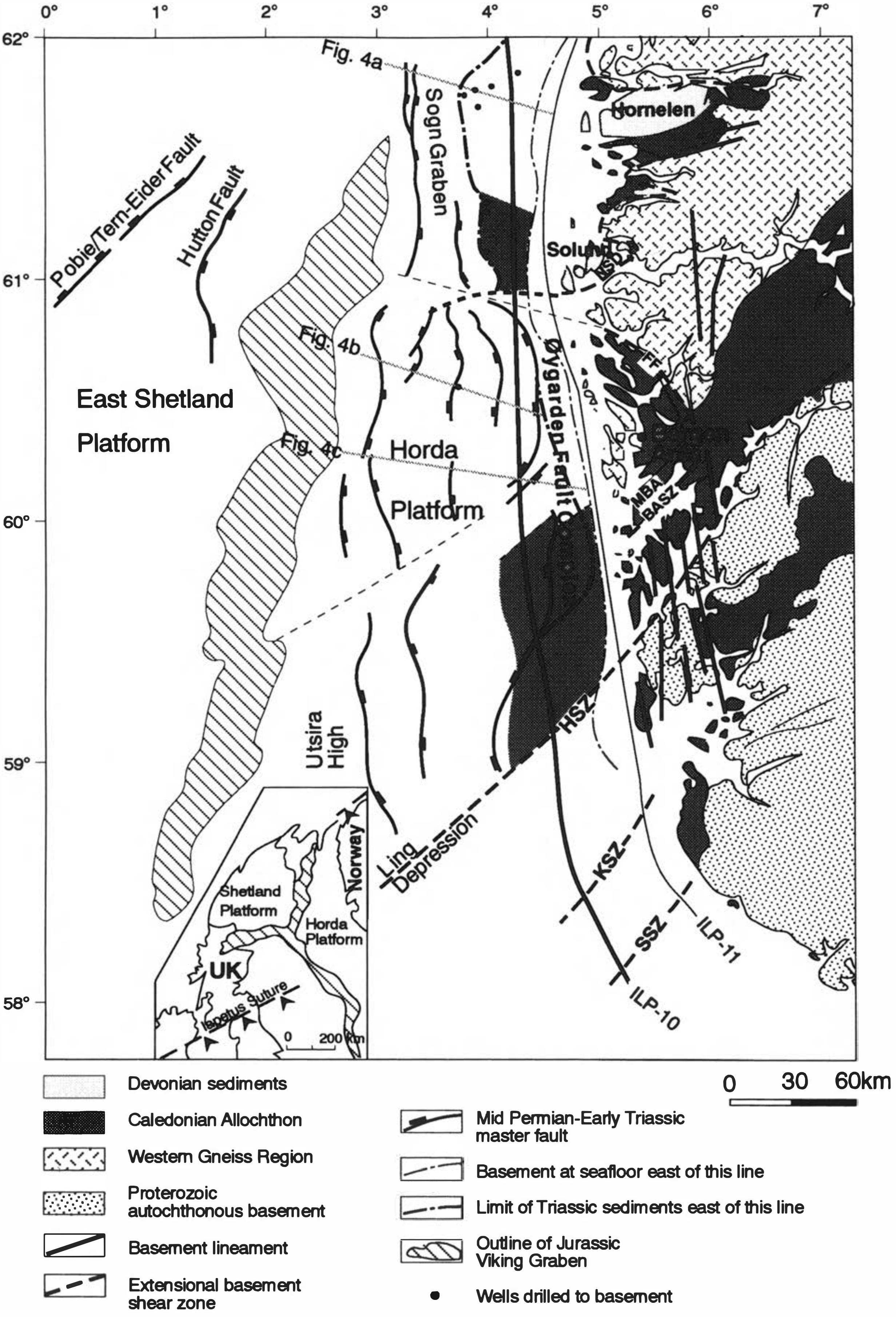
Introduction

The Øygarden Fault Complex represents a major structural divide in offshore southwest Norway. Immediately to the east of the fault complex, Precambrian and lower Palaeozoic rocks, typical of the Norwegian mainland, occur at seabed (Fig. 1). West of the fault complex these basement rocks, now at an estimated maximum depth of some 8–10 km, represent the substrate to the North Sea sedimentary basin. The Øygarden Fault Complex also marks a sharp transition in crustal thickness from the mainland to the adjacent Horda Platform (Sellevoll 1973; Hospers & Ediriweera 1991). The structural evolution of the North Sea region is generally considered as a multistage process; the initial development of the northwestern European margin during the late Precambrian–Palaeozoic was followed by intracontinental, Permian–Mesozoic stretching phases and concomitant thermal cooling and subsidence to produce the North Sea sedimentary basin.

As the North Sea sedimentary basin is built upon a crust that was involved in Caledonian collisional tectonics, and further is assumed to cross over the Laurentia–Baltica plate boundary (Iapetus Suture), it raises the question about the scale on which Caledonian structures were reactivated during later deformation phases. The effect of the basement trends on subsequent Mesozoic geometry in the North Sea, on a regional scale, was first suggested by Johnson & Dingwall (1981), and has later been treated by a number of authors (e.g. Beach 1985; Watson 1985; Frost 1987; Ziegler 1990a; Stewart et al. 1992; Bartholomew et al. 1993; Coward 1993; Williams 1993). It has been suggested that the complex architecture of the North Sea sedimentary basin is most easily explained by a NE–SW Caledonian grain exerting a fundamental control upon the style and geometry of the basins formed in response to later extension. However, the difficulty in such interpretations is that only rarely is it possible to be confident about the location of early Palaeozoic and older structures within the areas of deeply buried basement. Applying the results of deep seismic reflection surveys as well as magnetic and gravity data, depth to basement has been mapped over major parts of the northern North Sea (e.g. Klemperer 1988; Fichler & Hospers 1990; Hospers & Ediriweera 1991). However, depth to the top basement is generally poorly constrained, since basement reflections may not always be consistently identified throughout the area, and since the boreholes which reach basement and enable calibration of deep seismic events are few and generally located close to the basin margins. Another uncertainty involved in published models of the top basement is to what extent upper Palaeozoic rocks, which have not been


0°
1°
2°
3°
4°
5°
6°
7°
62°
61°
60°
59°
58°
Fig. 4a
Fig. 4b
Fig. 4c
Sogn Graben
Hornelen
Solund
NSDZ
FF
MBA
BASZ
Pobie/Tern-Eider Fault
Hutton Fault
East Shetland Platform
Horda Platform
Øygarden Fault Complex
Utsira High
Ling Depression
HSZ
KSZ
SSZ
ILP-11
ILP-10
Shetland Platform
Horda Platform
Norway
UK
Iapetus Suture
0 200 km
0 30 60km
Devonian sediments
Caledonian Allochthon
Western Gneiss Region
Proterozoic autochthonous basement
Basement lineament
Extensional basement shear zone
Mid Permian-Early Triassic master fault
Basement at seafloor east of this line
Limit of Triassic sediments east of this line
Outline of Jurassic Viking Graben
Wells drilled to basement

encountered to date may be present in the northeastern part of the North Sea basin.

The regional network of deep seismic reflection data (see Klemperer & Hurich 1990 for references) has been used by several workers to map crustal structures and the reflection Moho and, hence, the amount of crustal thinning in the area. A commonly made generalization about lithospheric reflectivity in northwest Europe is that, beneath sedimentary basins, the upper part of the crust is fairly transparent, the lower crust is highly reflective and the uppermost mantle is transparent. Cheadle et al. (1987) suggested that the reflective lower crust is typically associated with regions of extension, and seismic sections crossing from the North Sea basin to adjacent platform areas show indeed a variation from highly reflective to less reflective lower crust (McGeary 1987). However, newer deep seismic data have demonstrated reflective lower crust in a number of tectonic regimes, showing that models linking reflective character with tectonic history must be treated with caution (Klemperer & Hurich 1990).

The present crustal thickness of western Norway of about 32 km (Sellevoll 1973; Kinck et al. 1991) is taken to represent the pre-Permian crustal thickness of the whole North Sea region. As a result of Permo-Triassic and Jurassic extension the present-day crustal thickness is ca. 21 km and 25 km beneath the Viking Graben and Horda Platform, respectively, while pre-Triassic basement thickness is said to be about 15 km and 21 km for these two structural provinces (Klemperer 1988; Fichler & Hospers 1990; Hospers & Ediriweera 1991). Most workers have, however, realized that a discrepancy exists between the seismic and gravity Moho, where the seismic Moho appears to be somewhat deeper than the gravity Moho beneath the most severely extended regions of the North Sea basin (Fichler & Hopers 1990; Holliger & Klemperer 1990). It is generally stated (e.g. Klemperer & Hurich 1990) that the pattern of crustal thinning, following Permo-Triassic and Jurassic extension, is approximately symmetrical and centred beneath the main Viking Graben structure. Hence, the Horda Platform apparently retains a considerable thickness of basement crust, and is regarded as an area less affected by stretching than the adjoining Viking Graben.

In this account, the coast-parallel deep reflection profile ILP-10 (Fig. 1) recorded to 16 seconds, in combination with onshore and offshore data, is used to illustrate how the orientation, distribution and character of pre-existing structural grains ultimately controlled the geometry of the Permian–Mesozoic basins and faulted margins offshore southwest Norway. The autochthonous rocks, as well as those involved in the Caledonian deformation, show strong variation in both strike and dip in the coastal area of southwest Norway. Hence, the general assumption of a NE–SW Caledonian grain as the main controlling factor during subsequent extension and basin development represents a gross oversimplification which is only partly substantiated by available data. In addition, the structural model presented in this study for the eastern part of the northern North Sea suggests that a location of the main Permo-Triassic stretching centred beneath the Viking Graben is questionable.

Tectonic framework onshore and offshore southwest Norway

Northwestern Europe, a site of oceanic subduction and continental collision during the early Palaeozoic, underwent Devonian extension to form sedimentary basins. These events were followed by intracontinental stretching during the Permo-Triassic and Jurassic, producing the North Sea rift system. While the North Sea can be considered in broad terms as a series of linked, elongated half-grabens developed in response to dominantly E–W extensional intra-plate stress, the basement structure influenced the geometry of most Permian–Mesozoic basins and their faulted margins.

The Caledonian framework of south Norway may broadly be subdivided into three tectonic units: The Baltic Shield, a décollement zone, and an overlying orogenic wedge of far-travelled nappes which built up during convergence of Laurentia and Baltica in Ordovician–Silurian times. The regional-scale setting towards the end of the Caledonian orogeny is thought to have been a NW-dipping subduction zone underneath the Laurentian plate (Greenland) which resulted in subduction of the Baltic continental margin in Siluran times (Griffin et al. 1985; Roberts & Gee 1985; Andersen et al. 1991). Thrusting on the Baltic side of the orogen was characterized by a variety of thrust sheets with a distinct tectonostratigraphy, displaced from west to east onto the Baltoscandian platform (Andersen & Færseth 1982; Bryhni & Sturt 1985; Roberts & Gee 1985). The result was an orogenic belt with a crustal thickness approximately twice that of the original crust. Following late and post-Caledonian uplift, erosion and tectonic denudation, most of the upper plate (Laurentia) has been removed, exposing the basal décollement between the far-travelled nappes of the Caledonian Allochthon and the underlying lower-plate basement (Baltica). The autochthonous basement in southwest Norway (Fig. 1), which represents the

Fig. 1. Simplified geological map of southwest Norway, and regional Permo-Triassic structural framework of the northern North Sea. Seismic reflection profiles that are discussed are indicated. NSD – Nordfjord – Sogn detachment, BASZ – Bergen Arc shear zone, HSZ – Hardangerfjord shear zone, KSZ – Karmøy shear zone, SSZ – Stavanger shear zone, FF – Fensfjorden Fault, MBA – Major Bergen Arc. Inset: The Jurassic triple rift-system and the supposed trace of the Iapetus Suture on opposite sides of the North Sea basin. Arrows indicate dip of seismic reflections.

foreland of the orogen, is composed of Proterozoic plutonic rocks, migmatites and gneisses. These rocks retain their Proterozoic structural grain and isotopic signature showing little or no Caledonian overprint (Gorbatschev 1985). The basement rocks comprising the Western Gneiss Region (Fig. 1) are generally considered parautochthonous (Gorbatschev 1985), and present data indicate that these rocks are of Baltic affinity. The Western Gneiss Region was internally affected by Palaeozoic deformation and is characterized by increased strain intensity and metamorphic grade to the northwest (Griffin et al. 1985; Milnes et al. 1988). The Caledonian nappes of western Norway, which are an association of Precambrian rocks and lower Palaeozoic supracrustals, represent a series of progressively more far-travelled thrust complexes termed the Lower, Middle and Upper Allochthons (Gee et al. 1985; Roberts & Gee 1985). Remnants of a series of Caledonian nappes are preserved in structural depressions along the coast of southwest Norway (Fig. 1).

Orogenic increase in crustal thickness accompanied and followed by uplift, erosion and extension eventually resulted in restoration of normal crustal thickness. The Devonian basins located along the west coast of Norway north of 61°N (Fig. 1) are closely related to this process, and it has been suggested that the basins formed in the hanging walls of low-angle normal faults formed by reactivation of Caledonian thrusts (Hossach 1984; Norton 1986, 1987; Sèguret et al. 1989). Andersen et al. (1991) attribute the Devonian basins to gravitational instability and collapse of the syn-orogenic lithosphere, while Fossen (1992, 1993) asserted that early to middle Devonian plate divergence was necessary to explain the large-scale Devonian kinematic pattern of southern Norway. Nevertheless, Devonian top-to-the-west extensional transport is a common phenomenon in the Scandinavian Caledonides (Fossen 1992; Fossen & Rykkelid 1992, Gee et al. 1994; Hartz et al. 1994; Rykkelid & Andresen 1994), and the Nordfjord–Sogn detachment, the Bergen Arc and the Hardangerfjord shear zones (Fig. 1) are associated with these Devonian and west–northwesterly directed movements.

The youngest rocks encountered onshore southwest Norway are the alkaline dykes in the Hardangerfjord region, which are associated with N–S and NNW–SSE trending, regional fractures (Fig. 1) possibly representing a reactivated Precambrian structural grain. Spinel-lherzolite nodules appearing as xenoliths in such dykes, demonstrate a deep origin (70–80 km), thus indicating steep fractures on crustal scale (Færseth 1978). K/Ar measurements performed on amphibole and whole rock samples have demonstrated three episodes of dyke intrusion along recurrently opened fractures at around 275–255 Ma, 220 Ma and 160 Ma (Færseth et al. 1976). This indicates that the least principal stress axis may have been oriented approximately E–W over more than 100 Ma. Hence, magma tended to fill fractures to produce dykes in marginal parts of an extending terrain, during periods when normal faults were generated in the North Sea basin. Brecciation of dykes suggests younger fault activity (Færseth et al. 1976) and *in situ* stress measurements and seismological observations indicate present-day movements along these lineaments (Anundsen 1988; Gabrielsen 1989; Karpuz et al. 1990).

In the North Sea basin, phases of post-Caledonian extension have overprinted structures of the Precambrian and lower Palaeozoic basement. The Permo-Triassic and mid–late Jurassic rifting in the northern North Sea is considered to be a response to a regional stress regime having a least principal stress (σ_3) directed E–W to NW–SE. The clearest evidence for major early Triassic fault activity in the area is seen across the Horda Platform (Badley et al. 1984; 1988; Lervik et al. 1989; Gabrielsen et al. 1990). The timing of this rift phase is not well constrained, neither in the North Sea nor in the surrounding areas, although on East Greenland the onset of rifting is reported to be in the mid-Permian (Surlyk et al. 1984). The top of the syn-rift sequence, on the Horda Platform is suggested to be within the Teist Formation and is accordingly of Scythian age (Steel & Ryseth 1990). Consequently, the syn-rift phase encompasses less than 5 Ma of the earliest Triassic, which is a very short time period for a crustal stretching phase of this magnitude as compared to ca. 30 Ma (Bathonian–Volgian) for the Jurassic syn-rift phase. Hence, it seems plausible that stretching was initiated in the Permian. An assumption of a mid-Permian (ca. 260 Ma) initiation of fault movement, i.e. a syn-rift phase of minimum 20 Ma in the North Sea, is supported by the occurrence of Permian dykes in the southwest Norwegian coastal area (Færseth et al. 1976; Furnes et al. 1982) and a Permian palaeomagnetic age for reactivation of faults of the Nordfjord–Sogn detachment (Torsvik et al. 1992).

Middle and upper Triassic, lower Jurassic and middle Jurassic strata (a span of ca. 70 Ma) in the North Sea basin are termed post-rift and interpreted as representing a response to thermal subsidence following Permian–early Triassic stretching (Gabrielsen et al. 1990). Triassic sediments interpreted as post-rift show evidence of sedimentary growth towards the Øygarden Fault Complex. Combined with alkaline dykes of Carnian–Rhaetian age, which intruded steep N–S trending basement fractures in the outer Hardangerfjord area (Færseth et al. 1976), this indicates extensive tectonic activity along the basin margin. There are also significant thickness changes of Triassic (Steel & Ryseth 1990) and early–middle Jurassic (Yielding et al. 1992) sequences across some of the major faults within the basin. However, the most striking feature of the post-rift stratigraphy is the presence of some nine major clastic wedges, originating from the Shetland and Norwegian hinterlands. It has been argued that these reflect the pulsed nature of thermal subsidence/compaction in the post-rift interval (Steel 1993).

Renewed extension in the Jurassic in the northern North Sea was focused within the Viking Graben, which was a site of considerable crustal thinning at this time

(Klemperer 1988; Holliger & Klemperer 1990; Fichler & Hospers 1990). The structure of the northern North Sea, as defined on Jurassic levels, is dominated by master faults, with predominant N–S and NE–SW orientations (e.g. Færseth 1983), which define the large-scale tilted fault blocks. Sedimentary units (Viking Group) from the late middle Jurassic to the late Jurassic–earliest Cretaceous, exhibit wedge-shaped geometries adjacent to major faults, suggesting syn-depositional fault movements.

Structural features offshore southwest Norway (Line ILP-10)

The N–S oriented line ILP-10 shows a broad antiformal feature at upper and middle crustal levels, which culminates at ca. 60°N (Fig. 2). A similar feature was reported by Hurich (in press), based on interpretation of the deep reflection profile ILP-11, located east of the Øygarden Fault Complex (Fig. 1). The antiform is spatially and geometrically related to the Hardangerfjord shear zone and its associated half-graben (Fig. 5b). Extension, most likely of Devonian origin (Fossen 1992), was accommodated by movements along the Hardangerfjord shear zone, and rotation of the upper and middle crust produced the SE-dipping limb of the antiform (Fossen 1993; Hurich in press). Line ILP-10 (Fig. 2) demonstrates the influence of the antiformal feature also at higher stratigraphic (Jurassic–Cenozoic) levels (Fig. 3). In the northern part of the line, reflections with an apparent 30°–40° northwesterly dip are imaged in the middle and lower crust (Fig. 2). A culmination at upper and middle crustal levels, just south of the Nordfjord–Sogn detachment, (Fig. 2), could correlate with the antiform mapped by Milnes et al. (1988) in the outer Sognefjord area.

In both line ILP-10 (Figs. 2 and 3) and line ILP-11 (Hurich in press, his fig. 2), a localized thinning of the lower crust between 59° and 60°N is apparent. On the Horda Platform the reflection Moho is not unequivocally imaged, and reflectors occur beneath the Moho definition applied in this contribution. Also from other parts of the North Sea basin, reflectors have been reported beneath the interpreted gravity Moho (e.g. Fichler & Hospers 1990; Holliger & Klemperer 1990), indicating that uncertainties remain regarding the position of the Moho. Above the reflection Moho, the lower crust is reflective over a thickness of up to 10 km (Figs. 2 and 3). Below the permo-Triassic sediments, the upper crust is essentially transparent with the exception of areas where dipping reflections are identified. Apart from the Nordfjord–Sogn detachment and Hardangerfjord shear zone, which are represented by zones of dipping reflections, the events recorded in the upper crust within the study area may be reflections from lithological and structural interfaces within the basement.

The two deep seismic profiles (ILP-10 and ILP-11) reveal zones of dipping reflectors also outside the study area. South of the Hardangerfjord, reflection zones offshore Karmøy and Stavanger termed the Karmøy and Stavanger shear zones respectively, project onshore into a broad area of penetrative deformed basement rocks. Hurich & Kristoffersen (1988) interpreted the reflective

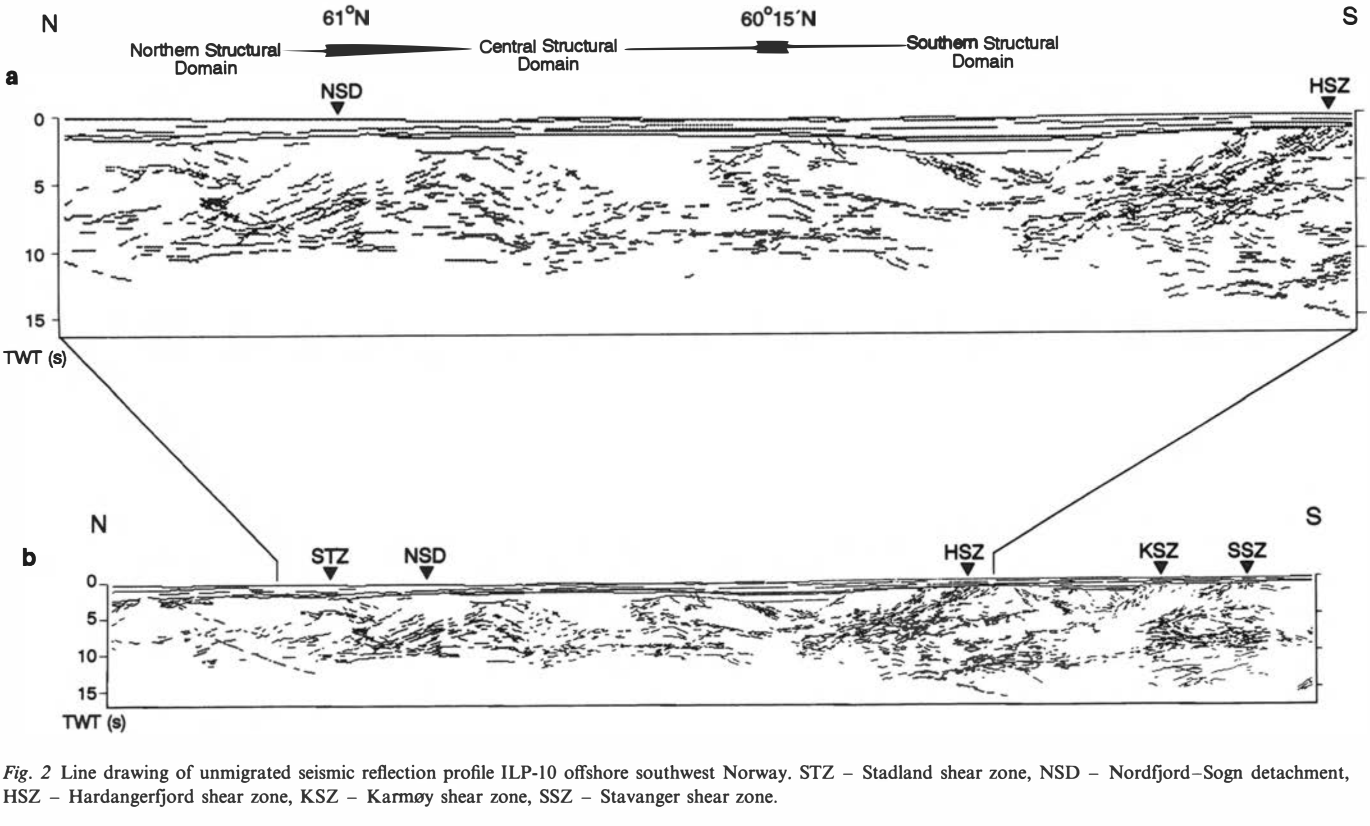


Fig. 2 Line drawing of unmigrated seismic reflection profile ILP-10 offshore southwest Norway. STZ – Stadland shear zone, NSD – Nordfjord–Sogn detachment, HSZ – Hardangerfjord shear zone, KSZ – Karmøy shear zone, SSZ – Stavanger shear zone.

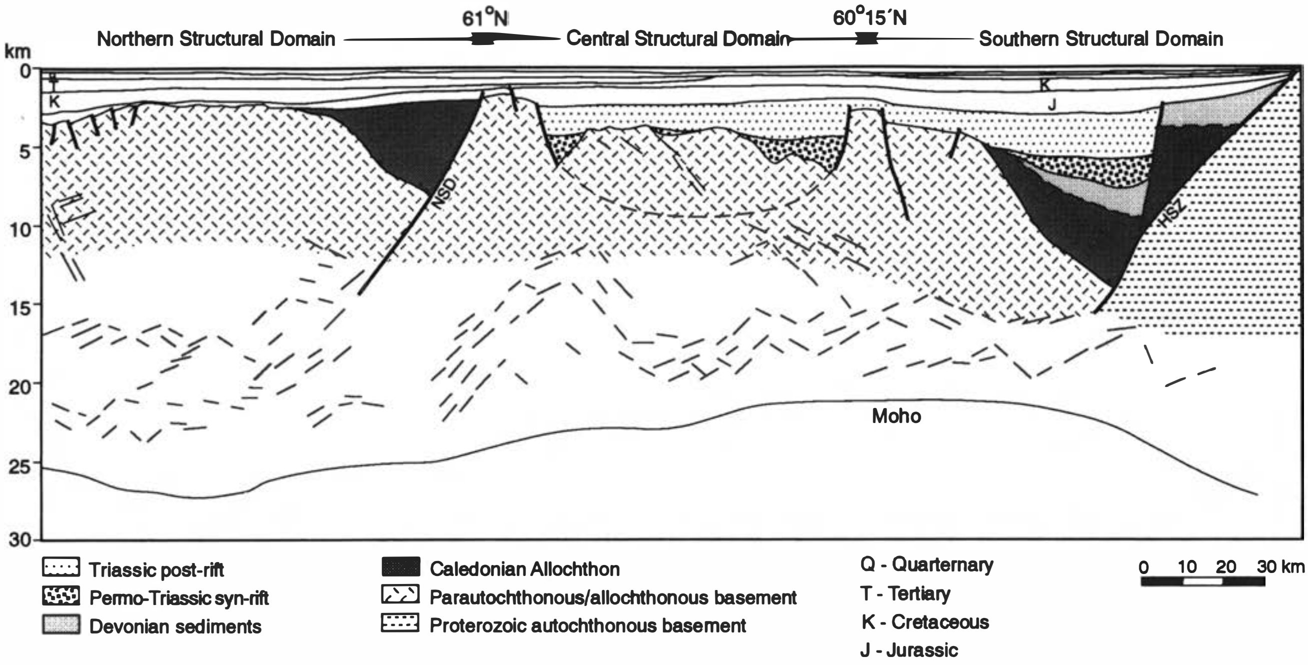


Fig. 3. Interpretation of the unmigrated, depth converted seismic reflection profile ILP-10. NSD – Nordfjord – Sogn detachment, HSZ – Hardangerfjord shear zone. Dipping reflections in the upper crust and reflections in the lower crust are indicated. Moho is defined by lowermost part of reflective band of the lowermost reflective crust. Vertical scale exaggeration × 3.75.

zones as Caledonian thrust faults that penetrate to lower crustal level in an area of thickened crust (Fig. 2b). The zone of northwesterly dipping reflections in the middle and lower crust, north of the Nordfjord–Sogn detachment is informally referred to as the Stadland shear zone (Fig. 2b) by Hurich (in press). North of this, reflectors in the middle and lower crust reveal dips both to the south and north.

Boreholes in offshore southwest Norway have encountered Caledonized Precambrian basement as well as meta-supracrustals, presumably of Cambrian–Ordovician age (e.g. Lervik et al. 1989). The wells can be tied to commercial reflection seismic data, and together these data sets indicate that contrasting basement lithologies have their characteristic seismic signature. Applying these characteristics as a guideline, it appears that variations in basement lithologies along line ILP-10 should be correlated to geological units onshore. As the seismic line ILP-10 is located relatively close to the basin margin (Fig. 1), basement is generally shallow, i.e. 2.0–4.0 km (Fig. 3). To the west, however, basement is either stepping down across normal faults (Fig. 4b) or dipping westward against east-dipping master faults (Fig. 4a, c). East of the Sogn and Viking Grabens, boreholes exhibit early Triassic units as the oldest sediments above basement. Where basement dips away from the coastline, progressively younger sediments (Triassic–Jurassic and locally Cretaceous) onlap the basement to the east (Fig. 4a, c). Permian, Carboniferous and Devonian rocks have not been encountered to date in wells drilled in the eastern part of the northern North Sea. It has, however, been suggested that the Devonian basins of western Norway may have extended west of the present-day coastline to form a continuous basin together with the Devonian sediments (Old Red sandstone) which underlie major parts of the UK East Shetland Basin (e.g. Norton et al. 1987; Ziegler 1990b; Coward 1993). The absence of Devonian sediments west of the Hornelen and Solund basins (Fig. 1) may indicate tilting and a period of deep post-Devonian erosion and deposition of Triassic and younger Mesozoic sediments above the erosional unconformity. It is likely that erosion was associated with mid-Permian–early Triassic crustal stretching, which reached a considerable magnitude ($\beta = 1.3–1.4$, Yielding et al. 1992) to the west of the Norwegian coastline. The crustal stretching generated faults which exhibit maximum throw of some 4–5 km, fault-block rotations of 6–7° and large-scale footwall uplift. Associated deep erosion exposed basement rocks on structural highs within the basin (e.g. well 31/6-1 on the Horda Platform, Figs. 1 and 4b), while upper Palaeozoic pre-rift as well as syn-rift sediments might be present within the deep half-graben structures.

The mid-Permian–early Triassic structural pattern west of southern Norway can be considered as a series of linked, opposing half-grabens related to basement-involved faults with a predominant N–S orientation (Fig. 1). However, as the pre-existing structural grain and contrasting basement lithologies gave rise to changing basin geometries along strike, the study area has been separated into three structural domains which are all transected by line ILP-10.

Northern structural domain (61°–62°N)

The most prominent event of this domain as seen in line ILP-10, is the asymmetric, E–W trending structural depression at basement level between 61° and 61°20′N (Figs. 1, 2 and 3). To the north of this feature the top basement represents a strong reflector at a depth of ca. 2.5 km. Boreholes and seismic data suggest that beneath this part of line ILP-10 the basement comprises heterogeneously Caledonized Precambrian rocks which can be correlated with rocks of the Western Gneiss Region (Fig. 1). These lithologies typically exhibit a rough surface in the offshore area, probably reflecting an uneven erosional, partly faulted topography (Fig. 3). South of 61°20′N the top of the basement is seen as southerly dipping reflections (Fig. 2). The overlying wedge, which reaches thicknesses up to 5.5 km, is terminated abruptly in the south by reflections dipping 25° to the north down to about 14–15 km depth (Figs. 2 and 3). Boreholes (Fig. 1) have revealed that at least the upper parts of this wedge are ascribed to a succession of metamorphosed volcanic and sedimentary rocks with clear resemblance to lower Palaeozoic rocks known to underly parts of the Devonian Solund basin. The top of the lower Palaeozoic basement, as defined in line ILP-10, is a strong reflector at ca. 2.0 km, while reflections below are considerably weaker.

The coastal area of western Norway shows a significant east–west lineament maximum north of Sognefjord (Ramberg et al. 1977) which is associated with folds and fractures in basement rocks and the boundary faults of Devonian sedimentary basins (Fig. 1). These basins have been associated with top-to-the-west transport on a lower–middle Devonian detachment (Hossack 1984; Norton 1986; Séguret et al. 1989), or as an array of extensional detachments (Andersen & Jamtveit 1990). The zone of main dislocation in onshore areas, which brought lowermost greenschist facies mid–late Devonian coarse-clastic sediments and early Palaeozoic rocks of the Caledonian Upper Allochthon into close contact with gneisses with Caledonian eclogite facies metamorphism, has been termed the Nordfjord-Sogn detachment (Norton 1987) (Fig. 1). The importance of this shear zone has been emphasized by Andersen et al. (1991) and Fossen (1992). Torsvik et al. (1992), based on palaeomagnetic data, claim that the semiductile to brittle Dalsfjord and Solund faults which truncate the detachment (Andersen & Jamtveit 1990) have undergone reactivation in Permian as well as in late Jurassic/early Cretaceous times. It is also notable that K/Ar (whole rock) dating of an ultrapotassic syenite dyke in this area gave mid-Permian ages between 261 ± 6 and 256 ± 5 Ma (Furnes et al. 1982), probably related to early magmatic activity associated with the Permo-Triassic phase of extension.

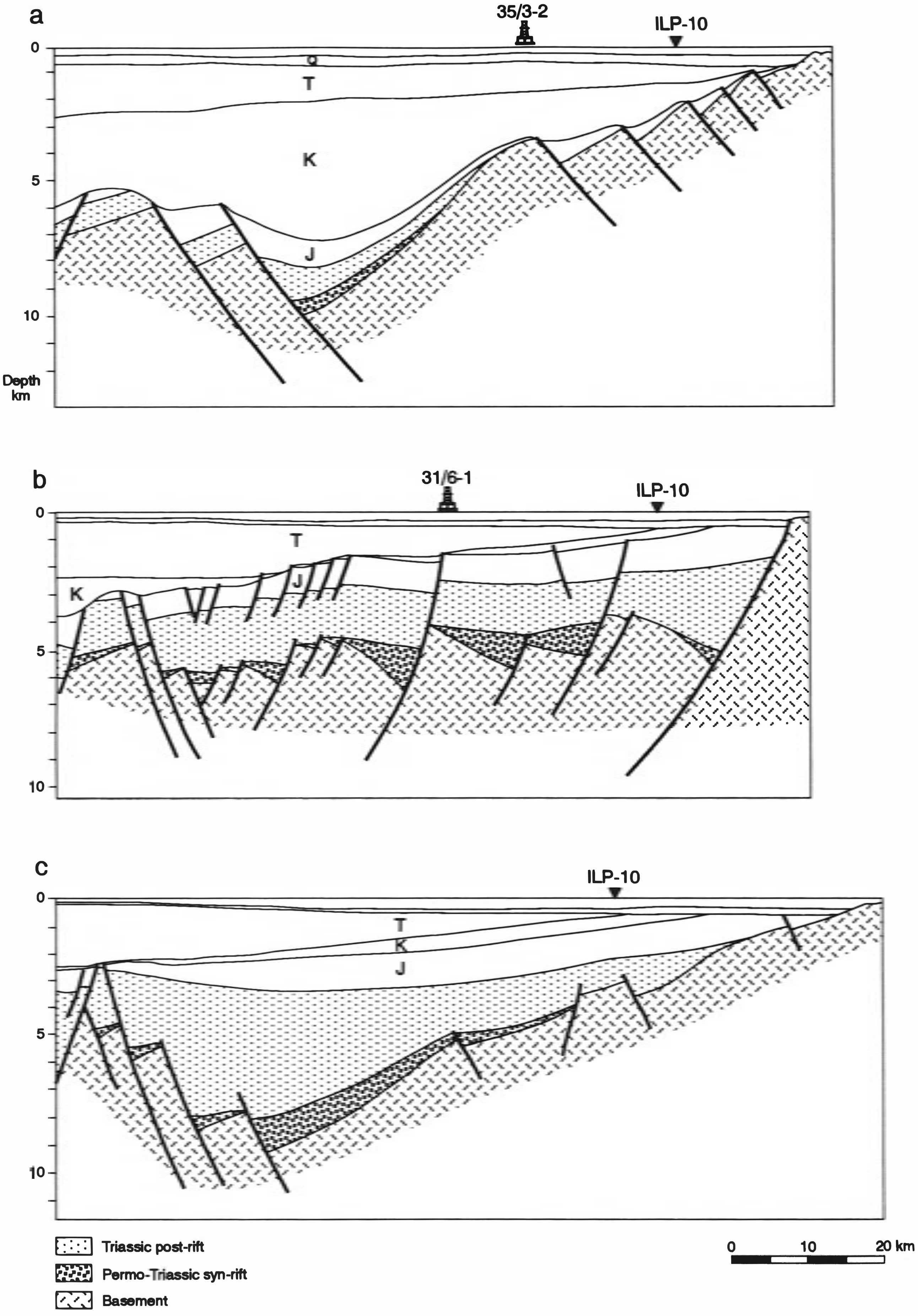
As stated above, Devonian sediments have not been encountered in the eastern part of the northern North Sea basin. Devonian sediments overlie basement above a basal unconformity on small islands to the west of the main basins of western Norway, which indicates that the base of the Devonian sediments is situated in a higher topographic position to the west. This could be attributed to block tilting (7–15°) associated with Devonian fault activity as suggested by Norton (1986). However, an increased effect of Permo-Triassic stretching and footwall uplift west of the present Devonian basins might have contributed to a deeper level of erosion and complete removal of Devonian deposits.

We suggest that the structural depression as identified on line ILP-10 represents the offshore continuation of the substrate to the Solund basin, and, hence, not the Devonian sediments themselves. The position of the north-dipping zone of reflections at 61°N, which represents the southern boundary of the structural depression, matches the offshore projection of the Nordfjord–Sogn detachment (Fig. 1). In the area under consideration it bounds a half-graben which apparently contains a considerable thickness of assumed lower Palaeozoic supracrustals. This boundary fault represents the interface between the lower Palaeozoic supracrustals and Caledonized Precambrian rocks which occupy the footwall to the south (Fig. 3). Like the onshore part of the Nordfjord–Sogn detachment, the fault is probably related to late/post-orogenic extensional movements. Although seismic evidence indicate that this E–W trending fault has not been significantly reactivated in the Permo-Triassic or Jurassic, it nevertheless represents an important, long-lived structural divide which affected late Palaeozoic and Mesozoic basin development. Deep Permo-Triassic half-grabens exhibit opposing geometries across this divide, which also influence Triassic as well as Jurassic sediment thicknesses. South of 61°N, the Horda Platform is almost unaffected by Jurassic stretching (Fig. 4b, c) which was focused further to the west at this point in time. However, north of 61°N, in the Sogn Graben area, pronounced Jurassic faulting is evident (Fig. 4a).

The large-scale structural pattern between 61 and 62°N, at Mesozoic levels, is controlled by an east-dipping fault zone representing the western boundary of the Sogn Graben (Fig. 1.) Permo-Triassic and Jurassic stretching phases and associated thermal subsidence have brought the basement down to about 9–10 km, resulting in a basement thickness of some 10–12 km in the deepest part of the Sogn Graben. The asymmetric nature of the graben gives rise to a westerly tilted basement (after adjusting for Tertiary uplift) east of the graben boundary fault (Fig. 4a). The tilted top basement surface becomes covered with progressively younger Mesozoic deposits to the east, and is overlain by lower Jurassic sediments along this northern segment of line ILP-10 (Fig. 3).

Central structural domain (60°15′–61°N)

The dominant onshore feature within this domain is the Bergen Arc System as defined by Kolderup & Kolderup (1940). It constitutes five rock units of different litholo-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10
20 km

gies and metamorphic grade, with tectonic contacts which show an arcuate outcrop pattern (Fig. 1). These units form an elongated structural depression, and result from a polyphasal deformation history during the Caledonian orogeny (Færseth et al. 1977; Thon 1985; Fossen 1988). NE–SW to NW–SE trends are associated with the Bergen Arc System. The parautochthonous Precambrian rocks (Øygarden Gneiss Complex) in the core of the system (Fig. 1), have a predominant N–S to NNW–SSE regional structural grain, although this is more complex on the field scale (e.g. Fossen & Rykkelid 1990). The eastern margin of the Bergen Arc System has been described as a major brittle structure containing kinematic indicators representative of down-to-the-west sense of shear (Fossen 1993). This zone of dislocation was termed the Bergen Arc shear zone by Fossen (1992). It incorporates the Fensfjorden Fault (Fig. 1) which marks the northeastern margin of the Bergen Arcs towards the Western Gneiss Region (Wenneberg & Milnes 1994), and has been suggested to represent the southward continuation of the Nordfjord–Sogn detachment (Milnes et al. 1988; Wenneberg & Milnes 1994).

Seismic lines reveal that basement rocks subcrop at seabed 5–10 km to the west of the coastline along this segment (Fig. 1). West of the subcrop line, it can be seen that the top of the basement dips gently to the west and at 4°20′E becomes vertically displaced 4–5 km across a major fault which is part of the Øygarden Fault Complex (Fig. 4b). This fault complex represents the divide between an eastern area, where the Caledonian crustal rocks apparently have retained their early Permian thickness, and a westerly area where post-Caledonian sediments in places exceed 8–10 km in thickness (compacted) and the basement crust shows considerable thinning following Permian–Mesozoic extension. The master fault at 4°20′E is part of an array of overall N–S trending faults across the Horda Platform which are typically 15–20 km apart and basement involved. The orientation and spacing of faults are comparable with N–S lineaments in the onshore Hardangerfjord area (Fig. 1). The only well drilled to basement in this domain (31/6-1), encountered Caledonized Precambrian gneiss overlain by syn-rift sediments of early Triassic (Scythian) age on the crest of a major, tilted fault block (Fig. 4b) and suggests significant uplift associated with the mid-Permian–early Triassic stretching phase to result in erosion of Palaeozoic rocks. On line ILP-10 the top basement reflector has the typical appearance of eroded crystalline basement. This may indicate that basement of the Horda Platform is correlative to rocks of the Øygarden Gneiss Complex which occupies islands west of Bergen (Fig. 1).

Seismic lines across the Horda Platform show that the principal extensional faulting (throws of 3–5 km on individual faults) occurred during the mid-Permian–early Triassic stretching, and that only minor displacement (<300 m) took place in late Jurassic–early Cretaceous time (Fig. 4b, c). The extension associated with the Permo-Triassic faulting is said to correspond to a stretching factor of 1.3–1.4, within this area, whereas the Jurassic–early Cretaceous reactivation has a $\beta < 1.05$ (Giltner 1987; Yielding et al. 1992). Roberts et al. (1993) suggested that the Jurassic–early Cretaceous effects observed in this area, represent subsidence associated with thermal cooling following Permo-Triassic stretching. Also Giltner (1987) suggested that a single (?) Permo-Triassic extensional event can explain almost all of the observed subsidence history on the Horda Platform. This implies a post-rift subsidence of some 240 Ma for this area and a decreasing subsidence rate with time. Depth-migration shows that the basement-involved faults on the Horda Platform have planar geometries (Yielding et al. 1991), although the present fault dip changes from typically 30°–35° in the basement to 40°–50° in the upper part where the faults cut through the sedimentary column and where dips are modified by compaction. Hence, the Permo-Triassic fault-blocks within the central structural domain, defined by evenly spaced and planar, basement-involved normal faults (Fig. 4b), have the characteristics of rigid block-rotation, i.e. the domino model of Barr (1987,a, b).

A major part of the central segment of seismic line ILP-10 represents the interior part of an easterly rotated fault block (Fig. 1). Top basement is found at a depth of 3.5–4.0 km and seismic data reveal basement partly overlain by middle Triassic post-rift sediments (Fig. 3). However, as the block-bounding master fault located to the east of the seismic line has an arcute shape in map view, imaging the onshore Bergen Arcs, line ILP-10 crosses this fault both to the north and to the south. As a corollary, the top of the crystalline basement along line ILP-10 dips towards the fault both to the north and south, and a syn-rift wedge is present and appears to overlie Caledonized Precambrian basement in the deep part of the half-graben (Fig. 3).

Line ILP-10 crosses two structural features at 60°55′–61°N and 60°10′–60°15′N where basement occupies anomalously high positions (Fig. 3). The northernmost of these basement highs is bounded to the north by a possible offshore continuation of the Nordfjord–Sogn detachment whereas the southern boundary has a NW–SE orientation. This trend parallels the Caledonian foliation typical of the Bergen Arc System as well as the Fensfjorden Fault in the onshore area (Fig. 1). Hence, in

Fig. 4. Cross-sections, drawn from depth converted reflection profiles, which illustrate the changes in mid-Permian–early Triassic basin geometries along strike. See Fig. 1 for location. Vertical scale exaggeration × 3.75.

this position the Permo-Triassic master fault, with an overall N–S orientation, curves and follows the NW–SE basement grain. Consequently, the basement high is an area which also became affected by Permo-Triassic footwall uplift. The continuation of this NW–SE trend is very pronounced also to the west of line ILP-10 (Fig. 1) based on commercial seismic data, and is interpreted to reflect the influence of a basement grain. To the south the master fault curves to a NE–SW orientation (Fig. 1). Correlations across the basement horst crossed by line ILP-10 at 60°10′–60°15′N, implies a strikingly large basement relief over a narrow structural feature (Figs. 1 and 3).

The Permo-Triassic master faults in offshore western Norway are both west and east dipping, and domains where such faults have a preferred dip direction can be identified (Fig. 1). Hence, the tectonic style is characterized by opposing, Permo-Triassic half-grabens, which is a well documented geometry of rifts. (e.g. Rosendahl 1987; Gawthorpe & Hurst 1993). High or low relief accommodation zones may develop due to semi-contemporaneous subsidence of opposite-dipping master faults along the graben margins, and the orientations of such accommodation zones tend to follow pre-rift structural trends. This concept has been applied on a regional scale in the North Sea basin (Scott & Rosendahl 1989; Morley et al. 1990). Offshore southwest Norway, the basement highs described above and transected by line ILP-10 are both located within accommodation zones related to Permo-Triassic extension. The master faults representative of the central domain exhibit consistent westerly throws in the eastern part of the Horda Platform across which the top basement is stepping down to progressively deeper level (Fig. 4b). These faults terminate along strike at approximately 60°15′N and 61°N (Fig. 1). To the north and south of these points, east-facing Permo-Triassic half-grabens and associated westerly dipping basement surfaces become dominant features (Fig. 4a, c). The change in fault polarity and the resulting accommodation zones are associated with basement grains represented by the Bergen Arc System and associated shear zone, and the Nordfjord–Sogn detachment.

Southern structural domain (59°–60°15′N)

The NE–SW striking Hardangerfjord of southwest Norway appears to form part of a long-lived and fundamental crustal structure that extends across southern Norway and continues to the SW into the North Sea basin. The Hardangerfjord lineament was first identified as a zone of major structural dislocation and termed the 'Faltungsgraben' by Goldschmidt (1916), and has later been described as a structural trough trending northeast into the axial depression of the Trondheim region (Roberts et al. 1970; Gee 1975; Ramberg et al. 1977). In the onshore area this lineament is possibly a Proterozoic tectonic contact (Gorbatschev 1985) related to accretion during the southwest Scandinavian orogeny (1750–1500 Ma) (Torske 1977; Falkum 1985). Hurich (in press) based on geophysical data, suggested that the Western Gneiss Region and the autochthonous Proterozoic basement of the foreland of the Caledonian orogen may be bounded by a Proterozoic suture along this lineament, which was reactivated as a Caledonian compressional feature as well as a Devonian shear zone. The rocks involved in Caledonian thrusting and folding and presently located on islands in the Hardangerfjord area, exhibit a dominant NE–SW structural trend on a regional scale (Færseth 1982; Nordås et al. 1985). Both the autochthonous and allochthonous rocks in the Hardangerfjord area are transected by N–S or NNW–SSE trending regional fractures which exhibit a spacing of 10–20 km (Fig. 1).

In the offshore area, the transition between the Caledonian foreland (Baltic Shield) and the hinterland is marked on the deep seismic lines by a ca. 10 km thick zone of reflections (Fig. 2) with an apparent dip of about 35° to the north (Hurich & Kristoffersen 1988; Klemperer & Hurich 1990; Hurich in press). The zone of reflections projects to the surface at the mouth of the Hardangerfjord (Fig. 1), and has been termed the Hardangerfjord shear zone in recent publications. The reflection seismic data indicate that the Hardangerfjord shear zone is associated with an observable change in depth to Moho (Fig. 5b, c) from about 28 km in the north to 34 km to the south on line ILP-11 (Hurich & Kristoffersen 1988). This lineament extends a minimum of 250 km southwest of the Norwegian coastline, and is termed the Ling Depression (Fig. 1) at Mesozoic levels (Brekke et al. in press). The presence of thick sediments underlying the Zechstein salt along the Ling Depression has been suggested (e.g. Hospers & Ediriweera 1991). This feature interferes with the NNW–SSE trending Central Graben, but a continuation further to the southwest to link with the Highland Boundary Fault of Scotland has, however, been suggested (e.g. Doré & Gage 1987).

The Bergen Arc shear zone is related to post-Caledonian, possibly Devonian westerly translation (Fossen 1992, 1993), like the Nordfjord–Sogn detachment and the Hardangerfjord shear zone. Based on interpretation of the seismic reflection line ILP-11 located ca. 10 km west of the coastline (Fig. 1), Hurich (in press) indicated a single half-graben comprising the Bergen Arcs as well as the Allochthon of the Hardangerfjord region, disregarding the Bergen Arc shear zone as a major structural feature in the offshore area (Fig. 5b). This may indicate that the Bergen Arc shear zone terminates east of line ILP-10 or that it continues to the south, possibly to merge with the Hardangerfjord shear zone. The half-graben identified on lines ILP-10 and ILP-11 is associated with south-dipping reflections (Fig. 2), and according to Hurich & Kristoffersen (1988) gravity modelling indicates that the Hardangerfjord shear zone is a post-Caledonian normal fault which presently bounds a half-graben assumed to contain up to 10 km of the

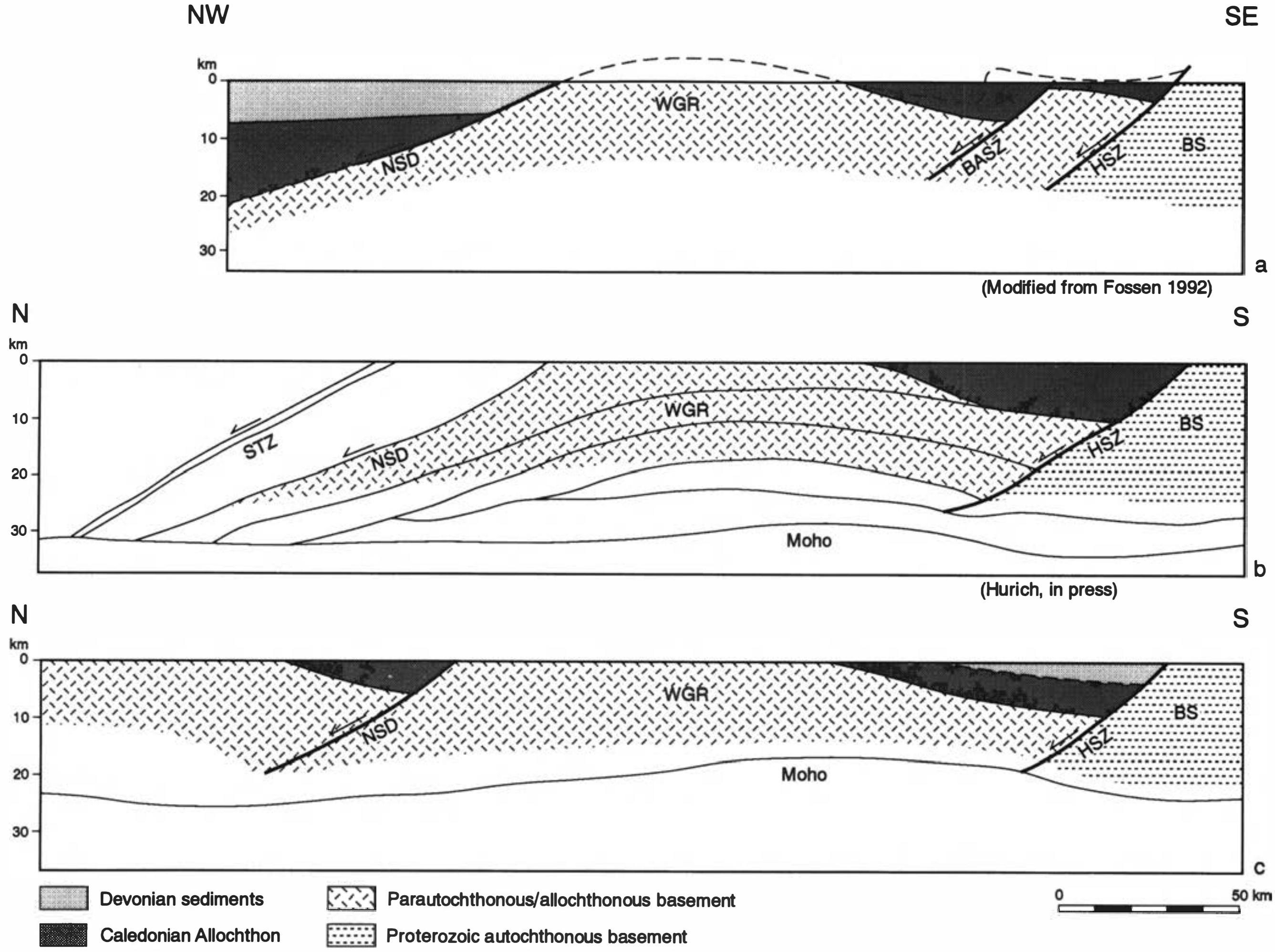

Fig. 5. Correlation between basement features in three transects representing both on- and offshore areas: (a) Structural features in the coastal area of southwest Norway (modified from Fossen 1992). (b) Interpretation of seismic reflection profile ILP-11 (Hurich in press). (c) Seismic reflection profile ILP-10 after removing post-Devonian sediments, showing main structural features at top basement level ca. 50 km west of the Norwegian coastline. NSD – Nordfjord–Sogn detachment, HSZ – Hardangerfjord shear zone. BASZ – Bergen Arc shear zone, STZ – Stadland shear zone, BA – Bergen Arcs, BS – Baltic Shield, WGR – Western Gneiss Region.

Caledonian Allochthon (Hurich in press). As the basement-cover contact is estimated to be displaced 2 km or more vertically across the Hardangerfjord shear zone in the onshore area (Fig. 5a) (Fossen 1992), the interpretation of the deep seismic reflection data (Fig. 5b, c) indicates either an increasing throw across this shear zone to the southwest or an underestimate of vertical displacement in the onshore area.

It is possible that down-to-the-NW movements on the Hardangerfjord shear zone were associated with deposition of Devonian sediments in the hanging wall. This assumption is supported by boreholes drilled to basement on the east flank of the southern Viking Graben, i.e. on the Utsira High (Fig. 1), located north of the Hardangerfjord shear zone. At this location, more than 400 m of deeply eroded Devonian sediments are preserved, and overlay lower Palaeozoic metamorphic rocks. Hence, the thick wedge-shaped body northwest of the Hardangerfjord shear zone assumed to represent the Caledonian Allochthon, may contain a considerable thickness of Devonian sediments on the Horda Platform west of the Øygarden Fault Complex, i.e. in an area where these rocks are unaffected by post-depositional uplift and erosion (Figs. 3 and 5c).

Shallow drilling has revealed a thin Jurassic sequence above basement immediately offshore the mouth of the Hardangerfjord (Rokoengen & Sørensen 1990). These sediments transgress the Hardangerfjord shear zone and appear to be unaffected by syn- or post-depositional fault activity. Hence, although the Hardangerfjord shear zone may have experienced some activity in the Permo-Triassic, the main displacement is ascribed to Devonian normal faulting.

As discussed above, the basement high at 60°10′–60°15′N on seismic line ILP-10 (Fig. 3) is located within a NE-SW trending accommodation zone related to Permo-Triassic extension. To the south of this feature, crystalling basement, as interpreted from its subcrop at seabed (Fig. 1), dips ca. 5° to the southwest, reaching depths which locally exceed 9 km west of line ILP-10.

The overall southwesterly dip of the top basement on the southern part of the Horda Platform results from block rotation and tilting towards N–S trending, Permo-Triassic master faults located west of line ILP-10 (Figs. 1 and 4c). These east-dipping faults imply that an accommodation zone exists between the southern and the central structural domains which are characterized by east and west-facing, Permo-Triassic half-grabens respectively (Fig. 1). At ca. 59°50′N and further south along line ILP-10, a wedge thickening to the south (Fig. 2) is interpreted as Palaeozoic rocks (Figs. 1 and 3) which in its northern part may represent an offshore continuation of the Major Bergen Arc. A Palaeozoic wedge in this position represents the westerly continuation of the half-graben established east of the Øygarden Fault Complex (Fig. 5b).

In the area between 59°N and 59°45′N a NNE–SSW-trending fault displaces the top basement with an increasing throw to the southwest. This fault is transected by line ILP-10 at 59°25′N (Figs. 1 and 3) and represents a Permo-Triassic master fault which locally follows the NE–SW trend of the offshore continuation of the Bergen Arcs (Fig. 1). The Permo-Triassic sediments exceed 4.5 km in thickness along this southern segment of line ILP-10 (Fig. 3) and increase in thickness to the west, which implies a thinning of basement to ca. 12–13 km within this area.

Discussion and implications

The deep reflection profile ILP-10, located ca. 50 km offshore southwest Norway, suggests that major basement units typical of the mainland can be identified west of the Øygarden Fault Complex. In the offshore area, these units represent the substrate of a sedimentary cover reaching thicknesses (compacted) of some 8–10 km. The coastal area of southwest Norway is characterized by an inhomogeneous basement both regarding composition and structural grain (Fig. 1):

- A regional NE–SW grain is represented by the Caledonian Allochthon in the Hardangerfjord area as well as the southern part of the Bergen Arcs. The Hardangerfjord and Bergen Arc shear zones related to Devonian extensional movements exhibit similar NE–SW trend.
- A NW–SE structural trend is represented by the Caledonian foliation typical of the northern part of the Bergen Arcs. The Bergen Arc shear zone incorporating the Fensfjorden Fault which defines the boundary towards the Western Gneiss Region defines a similar NW–SE trend.
- The Western Gneiss Region to the north is dominated by Precambrian rocks which suffered strong, but heterogeneous reworking during the Caledonian orogeny. A dominant E–W structural grain is associated with folds, fractures and boundaries of the Devonian sedimentary basins. The Nordfjord–Sogn detachment, influenced by this grain, represents a gently dipping Devonian shear zone below the basins.

The N–S trend typical of Permo-Triassic master faults in offshore southwest Norway as well as alkaline dykes of this generation which intruded steep, crustal-scale N–S to NNW–SSE-oriented fractures in the onshore area, are indicative of a predominant E–W extensional stress at this stage of development. Accordingly, the Permo-Triassic extension in the area under consideration affected a heterogeneous basement which was characterized by NE–SW, NW–SE and E–W grains resulting from Caledonian compression and Devonian extension. As these trends appear to be interrupted by N–S-oriented faults in offshore southwest Norway, it raises the question of whether the faults represent new structural features or whether these were generated through reactivation of a pre-existing (pre-Caledonian?) grain.

It is generally considered that, on a regional scale, pre-existing planar weaknesses like lithological interfaces, foliations and shear zones are likely to have a profound influence on the stress required for faulting to occur, and on the orientation of the faults that emerge. Hence, pre-existing zones of weakness oriented at high angles to the largest horizontal principal stress tend to be reactivated as normal faults, instead of new faults at an optimal orientation being generated (see Morley 1995 for references). Applying this concept, both the NE–SW and the NW–SE Caledonian trends of the southwest Norwegian coastal area potentially would be reactivated as normal faults during Permo-Triassic extension. However, the main effect observed in the study area is the change in polarity across some of these basement features together with local deviation from the overall N–S fault orientation. It appears that the critical stress level required to cause normal faulting along a N–S trend at this point in time was less than that required to reactivate Caledonian grains. As a corollary, we suggest that a pre-existing N–S structural grain was available and became reactivated by Permo-Triassic E–W extension.

N–S geological features are important elements of the Proterozoic autochthonous basement of southern Norway (e.g. Ramberg et al. 1977). In the coastal area of southwest Norway, N–S to NNW–SSE large-scale faults and fractures are most frequent in the Hardangerfjord region (Fig. 1), and they are assumed to be Precambrian elements which were rejuvenated and intruded by alkaline dykes. South of Hardangerfjord, the Karmøy and Stavanger shear zones (Fig. 1) project onshore into a broad area of penetrative deformed basement rocks to define an overall N–S trend. Further east the Proterozoic autochthonous basement is dominated by a regional N–S grain represented by lithological interfaces and fracture systems. The Mandal–Ustaoset Fault of south central Norway has a N–S extent of some 250 km on the mainland, and is described as a polyphasal Proterozoic terrain boundary (Sigmond 1985).

It may be speculated as to whether the N–S structural elements seen in offshore southwest Norway represent reactivated linear Precambrian crustal scale discontinuities. This implies that they have escaped the generally penetrative Caledonian deformation described from the coastal area, and at least partly retained their Proterozoic structural grain. Doré & Gage (1987) suggested that some of the deeply rooted regional lineaments of offshore Norway apparently maintained their linearity through complex deformation histories. We suggest that the zone which incorporates the Øygarden Fault Complex as well as the coastline of southwest Norway, is a potential site for a linear N–S discontinuity representing a Precambrian zone of crustal weakness. This zone exerted the main structural control during Permo-Triassic extension and development of the northern North Sea sedimentary basin. This assumption is based on the following observations.

- The Øygarden Fault Complex represents the most extensive (>300 km) N–S striking structural element in offshore western Norway. The orientation is discordant with the Caledonian grain typical of the mainland.
- The Øygarden Fault Complex marks a sharp transition in crustal thickness from the mainland to the adjacent Horda Platform.
- The Øygarden Fault Complex represented the main basin margin during both Permo-Triassic and Jurassic stretching phases. It remained active during periods when N–S-oriented faults further west were dormant.
- The Øygarden Fault Complex undergoes present day movements based on seismological observations and *in situ* stress measurements.

We will further argue that the deflection of the coastline, as well as the fault orientation in the offshore area at ca. 62°N, represents evidence for the strong influence of pre-existing basement grains. The location of the northern North Sea basin as a N–S structural depression at crustal scale suggests an increasing influence of an inherent N–S basement fabric offshore southwest Norway, which became reactivated by the E–W to NW–SE extensional phases related to Permo-Triassic and Jurassic rifting. The response of the same stress fields to the north of 62°N was the development of normal faults with a NE–SW orientation as a consequence of the strong control exerted by a pre-existing basement grain represented by the Møre–Trøndelag Fault Complex (Blystad et al. 1995).

The commonly held assumption that the structural evolution of the North Sea basin was controlled by a NE–SW Caledonian grain, reflects that the basin appears to cross over the Laurentia–Baltica plate boundary (lapetus Suture). The suture was located off the present northwest coast of Norway. West of the North Sea basin the supposed trace of the Laurentia–Avalonia lapetus Suture has been drawn with a NE–SW to ENE–WSW trend along the SE boundary of the Southern Uplands of Scotland, and to the east of Britain into the North Sea basin (see Klemperer & Hurich 1990 for references). Assuming a link between the two locations, now at opposite sides of the North Sea basin (Fig. 1 inset), and adjusting for the post-Caledonian extension across the basin, would suggest that the lapetus Suture was oriented NNE–SSW. This implies a Caledonian grain parallel to the Jurassic Viking Graben within the present northern North Sea basin.

Deep seismic reflection data reveal a considerable thinning of the crust within the northern North Sea basin. We suggest that basement thickness was reduced to about 12 km in places on the Horda Platform following Permo-Triassic extension. As stretching of this generation is estimated to $\beta = 1.4$ to the west of the Viking Graben (Yielding et al. 1992), i.e. comparable to the Horda Platform, it suggests that the extension at this point in time was distributed over the total width of the northern North Sea basin, while the Jurassic extension was much more localized and concentrated to the deep graben structures.

Most workers dealing with the tectonic evolution of the North Sea basin have assumed that the Jurassic triple rift-system comprising the Viking, Moray Firth and Central Grabens (Fig. 1 inset) originated during Triassic times and represented the main structural features also at this stage. However, as demonstrated above, the normal faulting in the Horda Platform area, characterized by large-scale activity during Permo-Triassic rifting, were not significantly reactivated in the Jurassic. Similarly, along the graben margins and also to the west of the Viking Graben, rare evidence (Hutton and Pobie/Tern-Eider fault, Fig. 1) exists for large Jurassic faults having been preceded by major activity in the Permo-Triassic, (Lervik et al. 1989; Færseth et al. 1994). It appears that, far from Permo-Triassic faulting being the precursor of the later Jurassic rifting, the two may have little spatial connection. We conclude that the mid-Permian–early Triassic extension, although distributed over a wide area, saw the highest fault activity concentrated to the eastern part of the basin. Hence, we are inclined to follow the suggestion of Vially (1988) that the main rift was situated on the present Horda Platform during this stretching phase. The orientation and architecture of Permo-Triassic structures within the eastern part of the northern North Sea basin were primarily controlled by reactivation of a possible Precambrian N–S grain, whereas the Jurassic Viking Graben further to the west has an overall NNE–SSW orientation and parallels the supposed trend of the Caledonian-age lapetus Suture within the North Sea region.

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