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Mega-scale Moho relief and the structure of the lithosphere on the eastern flank of the Viking Graben, offshore southwestern Norway

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Abstract The International Lithosphere Project deep reflection seismic survey in the Norwegian sector of the North Sea has been reprocessed, particularly focusing on the deep crust, the reflection Moho, and the upper mantle. The data display shifting reflection patterns of the crust and the upper mantle parallel to the eastern margin of the Viking Graben. In the upper crust, which is mainly seismically transparent by the processing techniques utilized here, large-scale structural features like detachment shear zones and master faults can be identified. Several of the major onshore faults and shear zones match seismic features in the seismic lines. Many of these structures acted as extensional shear zones in the Devonian. The middle crust is of variable reflectivity, whereas the *lower crust* is generally strongly reflective and is particularly so in the southern domain. The reflection Moho is identified throughout the study area but is of variable character. The presence of a S(E) dipping structure (Hardanger Moho Offset) that displaces the Moho by approximately 10 km, extends deep into the mantle (below the 50 km line depth), is positioned where the shallower Hardangerfjord Shear Zone, which flattens on the level of the middle crust, is situated. The Hardangerfjord Shear Zone/Hardanger Moho Offset-system coincides with change of the crustal thickness (depth to Moho), a change that also coincides with the transition from thin- to thick-skinned Caledonian deformation. Intramantle reflections are common in the study area, some of which are interpreted as shear zones, whereas others most likely represent magmatic intrusions.

1. Introduction

Detailed interpretation of the lower crust and the upper mantle from deep reflection seismic data is commonly difficult and controversial due to limited seismic resolution and the uncertainty of geological constraints [*Burg et al.*, 1994; *Brittan and Warner*, 1996; *Meissner*, 1996; *Culshaw et al.*, 2010; *Anahnah*, 2011; *Anahnah et al.*, 2012; *Jones et al.*, 2012; *Mandal et al.*, 2013]. Still, hard data for describing the lower crust and the upper mantle can sometimes be derived from outcrops of rocks that have been brought to the surface by tectonic and erosional processes [*Wernicke*, 1981, 1985; *Miller et al.*, 1983; *Allmendinger et al.*, 1987; *Block and Royden*, 1990; *Whitney et al.*, 2013; *Platt et al.*, 2015] together with potential field geophysical data [e.g., *Fichler and Hospers*, 1990b; *Holliger and Klemperer*, 1989; *Fichler et al.*, 2011], teleseismicity, and refraction or reflection seismic data [*Holliger and Klemperer*, 1989; *Marsden et al.*, 1990; *Christiansson et al.*, 2000; *Odinsen et al.*, 2000a]. Shortcomings of such data and methods limit our understanding of the lower crust and the upper mantle. Even for mature petroleum provinces richly covered by high-quality commercial seismic data and wells, such as the northern North Sea (Figure 1), our knowledge of the lithosphere beneath the petroliferous Mesozoic section is limited [e.g., *Klemperer and Hobbs*, 1991; *Nøttvedt*, 2000; *Evans et al.*, 2003; *Faleide et al.*, 2010]. Knowledge of prerift crustal structures (Proterozoic and Caledonian in the case of the North Sea) is important because they may have an influence on the structuring affiliated with subsequent rifting and thus on the distribution and nature of rift deposits [e.g., *Bartholomew et al.*, 1993; *Coward*, 1993; *Gabrielsen et al.*, 1999]. Hence, although the deep structure of the North Sea Basin System is known to some extent from several deep reflection- and refraction-seismic data sets [*Badley et al.*, 1984, 1988; *Barton and Wood*, 1984; *Beach*, 1986; *Beach et al.*, 1987; *Gibbs*, 1987a; *Giltner*, 1987; *Færseth and Pederstad*, 1988; *Klemperer*, 1988; *Fichler and Hospers*, 1990a, 1990b, *Holliger and Klemperer*, 1989; *Klemperer and Hurich*, 1990; *Marsden et al.*, 1990; *Hospers and Ediriweera*, 1991; *Færseth et al.*, 1995, 1997; *Christiansson et al.*, 2000; *Odinsen et al.*, 2000a, 2000b; *Evans et al.*, 2003; *Fichler et al.*, 2011], important questions concerning its lithospheric architecture remain

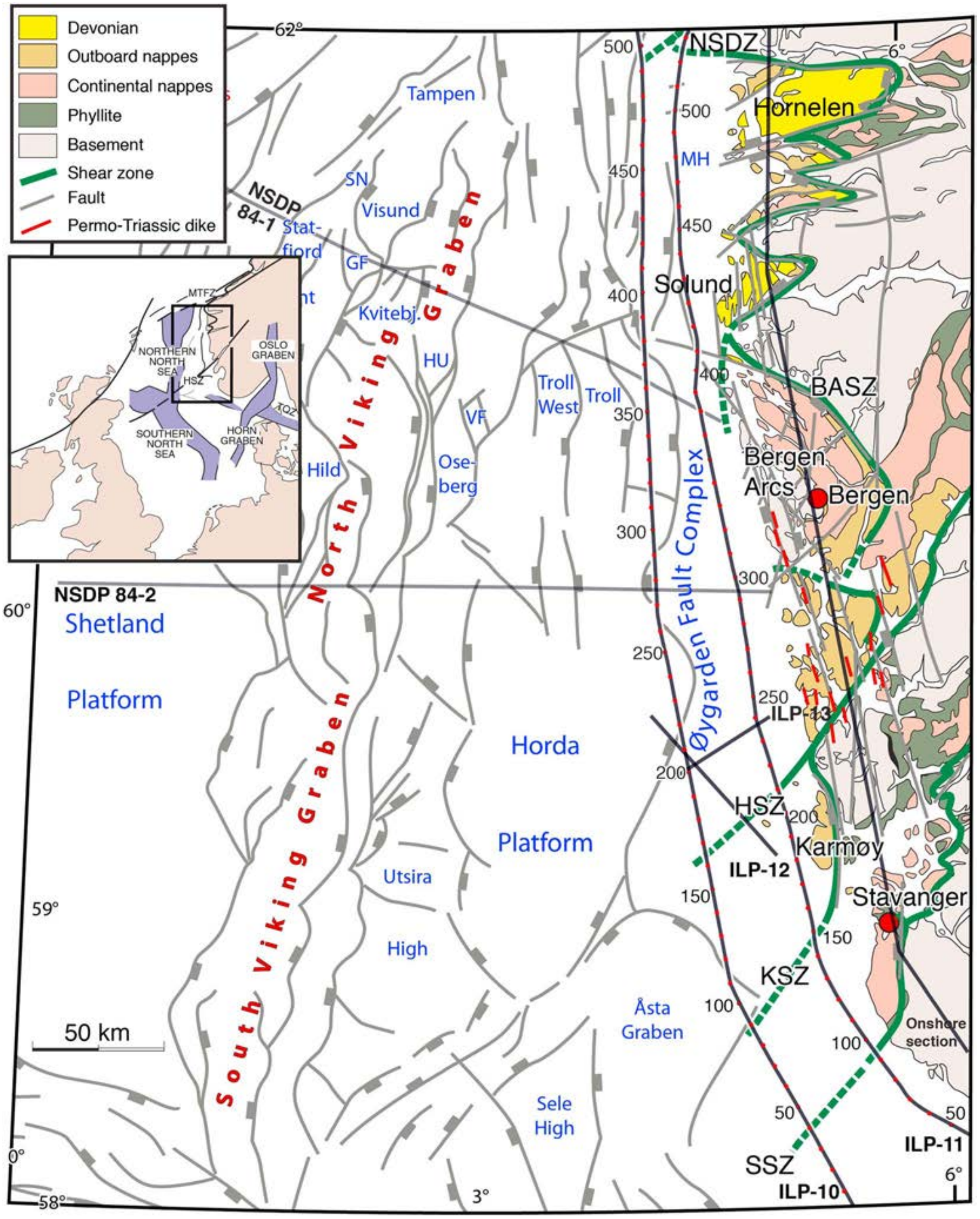

Figure 1. Structural map of the Viking Graben and adjacent Norwegian mainland with main structures and geological units/lithology. Seismic lines used in the present study (ILP-10 and ILP-11) are shown with reference numbers in km. See Figure 8 for 3-D geometry. Abbreviations: GF = Gullfaks, NSDZ = Nordfjord-Sogn Detachment Zone, BASZ = Bergen Arcs Shear Zone, HSD = Hardangerfjord Shear Zone, KSD = Karmøy Shear zone, MH = Måløy High, SN = Snorre, SSZ = Stavanger Shear Zone.

unanswered. Such questions include the configuration and the characteristics of the reflection Moho in some areas [*Holliger and Klemperer*, 1989; *Klemperer and Hurich*, 1990], the nature of the lower crust and the upper mantle [*Christiansson et al.*, 2000], the linkage between deep and shallow crustal structures [*Færseth et al.*, 1995], and structuring of the lower crust and the upper mantle [*Klemperer*, 1988; *Holliger and Klemperer*, 1989].

To obtain a better understanding of the lithospheric structure of the northern North Sea Rift, we here analyze reprocessed versions of deep seismic ILP (International Lithosphere Project) survey, which is characterized as an upper crust that includes the strongly reflective late Palaeozoic to Mesozoic-Cenozoic sediments and their

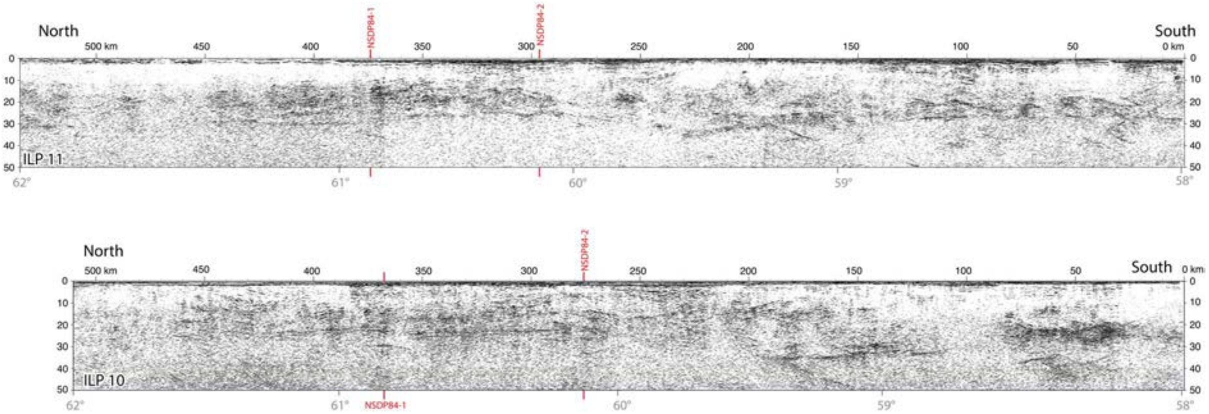

Figure 2. Uninterpreted N-S sections ILP-10 and ILP-11 offshore western Norway (seismic lines ILP-10 and ILP-11; **foldout**). See Figure 1 for location.

low-reflectivity (Proterozoic-Caledonian) basement (0 to approximately 15 km; Figure 2) The middle crust displays variable reflectivity and some high-reflectivity bands, whereas the lower crust is generally highly reflective displaying some segments of extreme reflectivity (particularly in the southern part of the sections). The Moho is generally well defined and is found between 25 (north) and 40 km (south). It separates the highly reflective lower crust from the mantle of less strong reflectivity (Figure 2).

2. Regional Setting

The North Sea rift system rests on a heterogeneous crust of Proterozoic and Caledonian age [*Gabrielsen and Ramberg*, 1979; *Gabrielsen et al*., 1999; *Slagstad et al*., 2011]. The latest stages of the Caledonian Orogeny were characterized by extension and gravitational collapse [*Fossen*, 1992, 2000; *Fossen and Dunlap*, 1998] and were followed by Permian to Early Triassic rifting and Late Triassic-Early Jurassic (postrift) subsidence. Permo-Triassic rifting is particularly well expressed on the Horda Platform and in the Shetland Basin [*Gabrielsen et al*., 1990; *Færseth et al*., 1995; *Odinsen et al*., 2000a], involving major faults like the Øygarden Fault Complex (Figure 1). The rift itself was dominated by a NNE-SSW structural grain, but also, faults with other orientations were present, some of which may be explained by reactivation of Proterozoic or Siluro-Devonian basement structures [*Gabrielsen et al*., 1999]. A major phase of rifting occurred in the Mid-Late Jurassic [e.g., *Gabrielsen et al*., 1990; *Færseth et al*., 1995; *Cowie et al*., 2005], rejuvenating parts of the established structural grain, and was accompanied by extensive postrift subsidence. [e.g., *Gabrielsen et al*., 2001; *Faleide et al*., 2002]. Thus, the N-S striking faults in the Horda Platform area, which were affiliated with the Permo-Triassic basin formation, became reactivated during the Jurassic-Cretaceous development of the Viking Graben [*Badley et al*., 1984, 1988; *Gabrielsen et al*., 1990; *Steel and Ryseth*, 1990; *Færseth et al*., 1995; *Nøttvedt et al*., 1995; *Færseth*, 1996].

Shear zones can be traced from the mainland and into the continental shelf of southwest Norway [*Gabrielsen and Ramberg*, 1979; *Færseth et al*., 1995; *Andersen et al*., 1999; *Fossen and Hurich*, 2005], of which several contribute to define distinct graben units in the context of *Scott and Rosendahl* [1989]. For example, the mostly Devonian Nordfjord-Sogn Detachment (NSDZ; Figure 1) is a conspicuous shear zone on the south Norwegian mainland, displaying evidence of reactivation in the Permian and Jurassic-Cretaceous [*Eide et al*., 1997, 1999; *Andersen et al*., 1999], juxtaposing ultrahigh-pressure gneisses of lower crustal affinity against very low-grade Devonian metasediments [e.g., *Norton*, 1986, 1987; *Andersen and Jamtveit*, 1990; *Hacker et al*., 2010].

It is generally assumed that the Caledonian crust was approaching normal crustal thickness by the time of Permian rifting [*Andersen and Jamtveit*, 1990; *Odinsen et al*., 2000a; *Gabrielsen et al*., 2010]. In the North Sea, the depth to the base of the crust in the North Sea is established by potential field data [e.g., *Frost et al*., 1981; *Hospers and Finnstrøm*, 1984; *Fichler and Hospers*, 1990a; *Hospers and Ediriweera*, 1991] and limited deep reflection seismic data [*Badley et al*., 1984, 1988; *Gibbs*, 1987a; *Holliger and Klemperer*, 1989; *Klemperer and Hurich*, 1990; *Odinsen et al*., 2000a, 2000b], showing crustal thinning from ~33–34 km on the flanks of the North Sea rift (Horda Platform, Shetland Basin) to 21–24 km beneath the Viking Graben [*Christiansson* *et al.*, 2000; *Evans et al.*, 2003]. The high-velocity body of the eastern margin of the rift system (8.1–8.4 m/s [*Christiansson et al.*, 2000; *Rosso*, 2007]) is concluded to be a part of the upper mantle for reasons discussed by *Fossen et al.* [2014].

2.1. Basement Onshore Southwest Norway

The onshore geology to the east of the study area is characterized by a Proterozoic basement that is overlain by remnants of the Caledonian orogenic wedge, now strongly eroded [*Naterstad et al.*, 1973; *Gee*, 1975; *Roberts and Gee*, 1985] and reduced to klippen in the southern part of Southern Norway [e.g., *Smit et al.*, 2011]. Southeast of Hardangerfjorden, the Caledonian deformation is thin-skinned [*Fossen et al.*, 2014] and the autochthonous basement consists of Paleaoeproterozoic and Mesoproterozoic continental rocks, which became reworked during the Sveconorwegian Orogeny, resulting in the initiation of five main "sectors." Some of these are separated by N-S trending shear zones [e.g., *Berthelsen*, 1980; *Bingen et al.*, 2001, 2005; *Andersen et al.*, 2002]. The model for the Mesoproterozoic suggests that a Proterozoic suture is situated in the North Sea southwest of Rogaland [*Bingen et al.*, 2005].

Northwestward from Hardangerfjorden, the basement (Western Gneiss Region) shows an increasing degree of Caledonian reworking and progressively higher metamorphic conditions. Pressures corresponding to burial depths in excess of 125 km [*Van Roermund et al.*, 2002; *Scambelluri et al.*, 2008] have been estimated for the Devonian ultrahigh-pressure terranes north of the Devonian Hornelen basin. This is consistent with a west or northwestward dipping Caledonian subduction zone, where the leading edge of Baltica was subducted underneath a wedge of detached island arc complexes and related units and, to the west, the Laurentian margin.

The Caledonian basal thrust was reactivated as a low-angle normal shear zone shortly before 400 Ma [*Fossen and Dunlap*, 1998], and several west and northwest dipping extensional detachments formed as this shear zone were rotated into a subhorizontal position, unfavorable for continued shearing. The Devonian extensional detachments include the major Nordfjord-Sogn Detachment, the Bergen Arcs Shear Zone, the Hardangerfjord Shear Zone, the Karmøy Shear Zone [*Bøe et al.*, 1992], and the Stavanger Shear Zone (Figure 1). The Hardangerfjord Shear Zone (HSZ; originally termed the Faltungsgraben [*Goldschmidt*, 1912, 1916]) is one of the most prominent post-Caledonian extensional structures in the study area, offsetting the top of the Proterozoic basement and its overlying Caledonian nappe pile by up to 10–15 km in a down to NW sense. Such structures are probably related to the collapse of the Caledonian Orogen and are characterized by reactivation in Permian and Mesozoic times [*Andersen et al.*, 1999], largely coeval with the major phases of extension in the northern North Sea rift system.

The onshore extensional shear zones have N-S to NW-SE orientations for the most part, some being curved and corrugated, notably the Nordfjord-Sogn Detachment, which also has four Devonian basins located in the detachment troughs. These are accordingly supradetachment basins with easterly dipping beds. The Hardangerfjord Shear Zone is currently dipping ~20–25° to the NW and flexes the Caledonian allochthons into a monoclinal structure that has been interpreted as a fault-propagation monocline [*Fossen and Hurich*, 2005]. This monocline is breached by the brittle Lærdal-Gjende Fault, and the Hardangerfjord Shear Zone extends into the North Sea where it can be recognized as a structural lineament that line up with the Highland Boundary Fault in the UK [*Doré and Gage*, 1987; *Færseth et al.*, 1995; *Fossen and Hurich*, 2005]. Although the Hardangerfjord Shear Zone clearly records significant Devonian offset, the 5–10 km thick package of seismic reflections that characterizes this zone offshore is thick for its 10–15 km Devonian displacement; hence, it is likely that it formed by reactivation of a Proterozoic shear zone [*Fossen and Hurich*, 2005].

The Lærdal-Gjende Fault is one of many NE-SW trending post-Caledonian brittle faults that affect SW Norway, of which many appear to have been established prior to the formation of the many coast-parallel fractures and dikes that dominate the coastal area [*Fossen*, 1998]. While the NE trending set largely recorded the Devonian NW-SE extension direction [*Chauvet and Séranne*, 1994; *Fossen*, 1998], the coast-parallel set hosts Permo-Triassic dikes [*Færseth et al.*, 1976; *Færseth*, 1978; *Fossen and Dunlap*, 1998] that suggest E-W extension consistent with early North Sea rifting [*Færseth et al.*, 1995; *Fossen*, 1998].

There is also isotopic and paleomagnetic indications of Permian and Late Jurassic/Early Cretaceous reactivation of Devonian extensional detachments/shear zones [*Eide et al.*, 1997], resulting in both low-angle and steep structures such as the Fensfjord Fault [*Wennberg et al.*, 1998], the Solund Fault, and the

Dalsfjord Fault, which contributes to the Måløy Horst. In addition, K-Ar dating of fault gouge illite suggests that onshore faults with a variety of orientations were repeatedly reactivated after the Devonian, with indications of poorly defined peaks around the Late Devonian/Early Carboniferous, Permian, Late Triassic-Early Jurassic, and late Jurassic/early Cretaceous [*Ksienzyk et al*., 2014].

3. Data Processing and General Characteristics

The present study is based upon reprocessed versions of the two N-S-oriented scientific lines ILP-10 and ILP-11 (Figures 1 and 2) and two short crosslines presented in *Fossen and Hurich* [2005], ILP-12 and ILP-13. These long-offset lines, which were recorded to 16 s two-way time, were acquired in 1988 in cooperation between the "Mobil Search" venture and the Norwegian branch of the International Lithosphere Program [*Klemperer and Hurich*, 1990]. The ILP lines, which were designed to image the lower crust and the upper mantle, were reprocessed poststack including time-migration, coherency filtering, tuning of bypass filters and depth conversion at the memorial University of Newfoundland (Canada) further to improve lower crust reflectivity. Migration and depth conversion were performed applying velocity information derived from co-located wide-angle data [*Deemer and Hurich*, 1994]. The processing of the seismic data followed a standard seismic reflection processing flow, which included poststack time migration and coherency filtering. Velocities for the time-depth conversion were derived from forward modeling of high-resolution, wide-angle seismic profiles, which recorded the shots used for the reflection data. Velocities increase from 5.9 km/s near the surface to 6.6 km/s in the lower crust with very modest lateral velocity variation along the profiles. Given the limited lateral variation in velocity, we are confident that the Moho step imaged in the seismic data is a function of the crustal structure and not due to the time-depth conversion. For correlation, the commercial deep lines, North Sea Deep Profile 1 and 2 [*Christiansson et al*., 2000; *Odinsen et al*., 2000a], were included in the study. The original lines (not depth converted) were presented by *Hurich and Kristoffersen* [1988], and lines ILP-10 and ILP-11 were used in a regional interpretation of the basement structures offshore south Norway by *Færseth et al*. [1995].

Ties to offshore wells that have been drilled to basement have been used in the interpretation based on information posted by the Norwegian Petroleum Directorate, and basement cores from wells 17/3-1, 18/11-1, 31/6-1, and 36/1-1 were inspected. In addition, information has been available for uncored basement wells 9/4-5, 32/4-1, 36/7-2, and 6204/10-1 [see also *Slagstad et al*., 2008, 2011].

The general lithospheric architecture of the two N-S striking reprocessed Mobil Search lines ILP-10 and ILP-11 is comparable to that portrayed by similar data elsewhere in northwest Europe [*Klemperer*, 1988; *Klemperer and White*, 1989; *Blundell*, 1990; *Evans et al*., 2003]: a upper crust of variable reflectivity, a reflective (locally highly reflective) lower crust, and variable Moho with local mantle reflections (Figure 2). The repossessed data surveyed here, however, allow us to go into more detail when it comes to variations in reflectivity and reflection patterns, notably of the reflection Moho, the lower reflective lower crust, and the reflective pockets of intramantle bodies and surfaces.

In general, we recognize the reflection Moho as a fairly consistent feature throughout large parts of the study area and use this as a surface of reference in the interpretation and description. It is locally clearly correlable to the top of the established 8.1–8.4 m/s layer on the east margin of the Viking Graben (Figures 2 and 3). Still, the Moho signature varies considerably, and in general, the reflection Moho is strongest where the lower crust is highly reflective, which means the southern parts of the study area (southern domain; see description below). The lower crust and the upper mantle display a variety of reflection signatures, and the reflection band associated with Moho is of variable continuity and signature. The mantle lithosphere of the northern North Sea is well known to contain features that set up strong reflections. Some of these reflections are believed to represent deep shear zones [*Beach*, 1986; *Gibbs*, 1987a, 1987b; *Klemperer*, 1988; *Klemperer and White*, 1989; *Færseth et al*., 1995; *Christiansson et al*., 2000; *Odinsen et al*., 2000a, 2000b]. Contrary to some previous reports, we have found that major shear zones also crosscut and displace the reflection Moho by several kilometers in some cases. We also find highly reflective intramantle zones that occur in isolation from the shear zones, both those previously reported and those mapped exclusively by us. Some of these features have are linear (planar, whereas others have the geometry and reflective characteristics of (intrusive?) rock bodies rather than faults [*Blundell*, 1990; *Anahnah*, 2011]. Some such bodies (linear) probably represent zones of particular texture, composition or fluid context (linear), or rock bodies of contrasting qualities

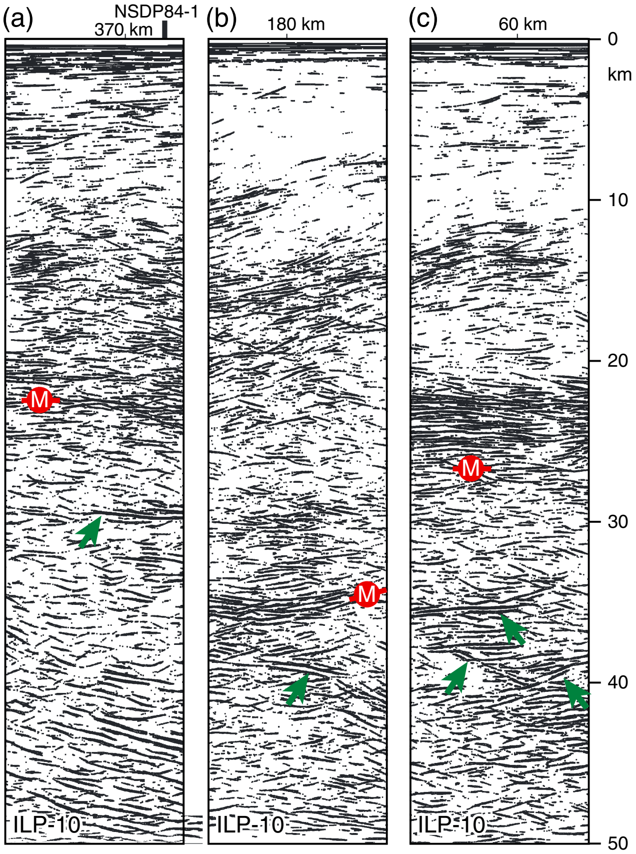

Figure 3. Comparison of typical reflection profiles for the (a) northern, (b) central, and (c) southern domains (Domains 1–3; see text and Figure 4). "M" identifies our interpretation of reflection Moho in each case. The arrows point to intramantle reflections. See Figure 1 for location and text for detailed descriptions.

(mineralogical/metamorphic) to that of the neighboring rocks. In the following, we have separated the descriptions of assumed shear zones that crosscut Moho from those that are confined to the mantle.

The middle and lower crusts [e.g., *Ranalli*, 1995; *Fowler*, 2005] are displayed as moderately to highly reflective in the present data. It should still be noted that the reprocessing was tuned particularly to image the deeper parts of the crust, so that the deep crust and the mantle reflectivity are enhanced and the reflectivity of the upper crust is suppressed.

The shallowest part of the crust displays the Late Paleozoic to Cenozoic sedimentary sequence of the North Sea basin system. This section is almost absent in the easternmost line (ILP-11), while it is characterized by variable reflectivity in ILP-10 (Figure 2). The structure of the uppermost part of the sections is well known through commercial seismic data and a great number of exploration and production wells. Although the shallow to middle parts of master faults and shear zones of the study area can be identified in the present data, the continuation of these structures deeper into the crust is not always clear.

The middle crust and basement rocks that partly were mobilized during the Caledonian Orogeny have been given attention in previous studies of deep reflection seismic data [e.g., *Klemperer*, 1988; *Klemperer and White*, 1989; *Færseth et al*., 1995] and provide information on the roots of the regional master fault systems [*Fossen and Hurich*, 2005].

In summary, the upper crust is not well imaged in the present data, but its stratigraphy, sedimentation history, and structure are well documented from an extensive number of commercial wells and reflection seismic data sets. The middle crust is generally clearly imaged but displays variable thickness and reflectivity. The lower crust and the reflection Moho display the most significant variance. The northern part of the study area is characterized by very variable reflection intensity of the lower crust and is also affiliated with a reflection Moho of variable reflectivity, whereas the southern part displays a very distinct reflection Moho and a remarkably reflective lower crust (Figure 2). Although this subdivision generally can be applied with some modifications in the study area, the regional variance along the strike of lines ILP-10 and ILP-11 is still considerable. For the study area, a threefold domainal subdivision is substantiated (the northern, the central, and the southern domains, Domains 1–3 from north to south; Figures 3, 4b, and 4c). This definition of the central domain (Domain 2; Figures 3 and 4, see below) is based on the identification of this domain as a zone characterized by swarms of dipping reflections (shear zones) that coincide spatially (in the surface projection), roughly with the offshore extension of the Hardangerfjord Shear Zone [*Fossen et al*., 2014]. In addition, there is a significant change in depth to Moho across the central domain, with Moho being situated much deeper in the southern as compared to the northern domain.

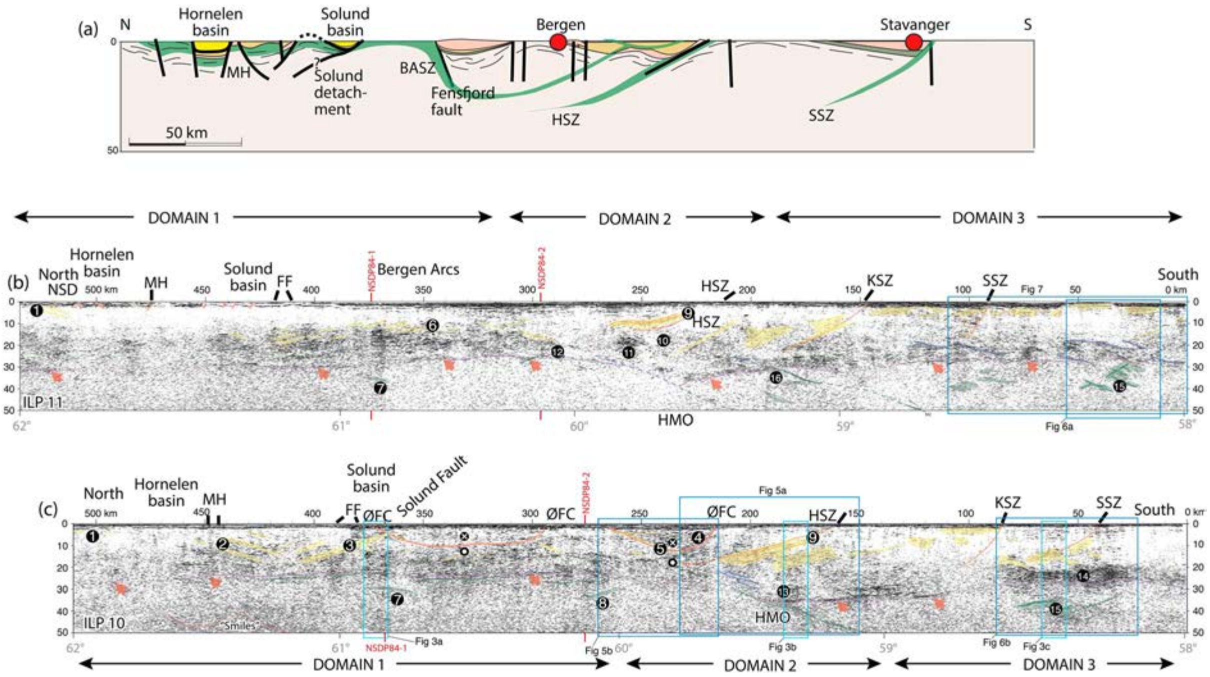

Figure 4. (a) Onshore structural profile and interpreted seismic lines (b) ILP-11 and (c) ILP-10. The locations of major features described in the text are marked with abbreviations (structures) and numbers (reflections). Trends of reflections are marked in yellow (upper crust), blue (middle crust), and green (lower crust). Note the clear but discontinuous reflection Moho and its down to the south offset in the central part of both lines ILP-10 and ILP-11, the distinction in reflectivity between the upper, middle, and lower crusts, and the extremely high reflectivity of the lower crust in the southern part of line ILP-10. See Figure 1 for locations and text for further description. ØFC = Øygarden Fault Complex. For other abbreviations, se caption to Figure 1.

It should be noted that this subdivision is somewhat different from that utilized by *Færseth et al*. [1995].

In the following description, specific observations on the interpreted line (Figure 4) are indicated in the figure notation as an additional number or abbreviation given after semicolon (e.g., Figure 4a, **markers yy (number-) and ZZ (letter**-) codes).

3.1. The Northern Domain (Domain 1; the Caledonian Tectonic Regime)

The northern domain (Domain 1; Figures 4b and 4c) is characterized by variable reflectivity and variable discontinuity of horizontal reflections. Sets of dipping, sometimes spoon-shaped reflections, occur in the upper crust of ILP-10 (Figures 4b and 4c, **markers 1–3**), some of which represent segments of the Øygarden Fault Complex (Figures 1 and 4b, **marker ØFZ**). This feature delineates the sediments of the Horda Platform from the basement of the southwest Norwegian mainland and crosses in and out of the ILP-10 line. The traces of these segments are correlable with commercial 2-D seismic lines. The hanging walls of some of the fault segments have accumulated up to 5 km thick pile of Mesozoic-Cenozoic deposits.

The northern part of the northern domain displays a less reflective middle and lower crusts than does the southern part of the domain. However, several sets of dipping reflections that may represent dipping gneissic layering or major fault zones are still seen. In the north part, south dipping reflections, possibly corresponding to the Nordfjord-Sogn Detachment (Figures 4a and 4b, marker NSD). Farther south, near the westward projection of the Meløy High, a prominent set of south dipping reflections are seen in ILP-10 (set 2 in Figures 4a and 4b, **marker MH)** interpreted as mylonites associated with Caledonian thrusting by *Reeve et al*. [2014]. Hence, the reflection pattern gives the impression of a large-scale trough geometry into which the Devonian basins project. Several restricted, lozenge-shaped zones of enhanced reflectivity in the middle and lower crusts appear in the northern domain. The geologic significance of these features is, however, not clear. A culmination between north and south dipping reflections around (Figure 4b, **marker 6**) is seen in ILP-11. It is tempting to correlate this antiformal structure with the core of the Bergen Arcs, which defines an ~50 km wavelength east plunging antiform.

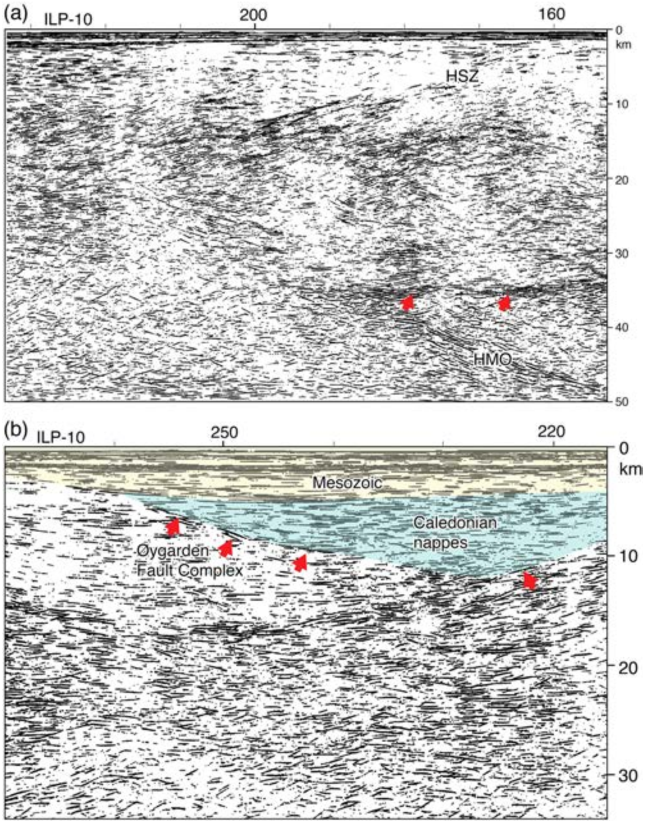

Figure 5. Lower crust with irregular reflection pattern and linear intramantle reflections of the Domain 3. (a) The Hardanger Moho Offset. (b) Reflection of one strand of the Øygarden Fault Complex, which strikes parallel to the ILP-lines.

The seismic expression of the *lower crust* in Domain 1 is generally strong, where the reflection Moho is well imaged, and otherwise much more transparent. A strong band of reflections, with a more transparent zone above it, is several places seen around 5 km above Moho (Figures 4b and 4c, **marker 14**), defining the top of the lower crust. In general, the lower crust is less reflective in the northern domain as compared to the southern domain (see below). The lower crust is of variable thickness, thinning to the north and toward the Domain 2. This thinning coincides with a southerly dip of the reflection Moho and is, in some places, associated with apparent shear zones? (Figure 4b, **marker 6**).

The reflection Moho in the northern domain is characterized by a broad band of reflections. This band of reflections becomes stronger but thinner toward the south (Domain 2), (Figure 4). A recent study [*Rosso*, 2007] has confirmed that Moho coincides with the shallower reflection as seen in the Domain 1. The fact that the reflection band of the lower crust/upper mantle envelops a high-velocity body in Domain 1 has lead to discussions regarding the depth, nature, and significance of the reflection Moho on the eastern margin of the northernmost North Sea [*Olafsson et al.*, 1992; *Christiansson et al.*, 2000; *Ebbing et al.*, 2006; *Breivik et al.*, 2011]. New analyses of gravity data give support to the idea that the geophysical Moho coincides with the shallower of the two alternative reflections discussed above, implying that the high-velocity rock body is a mantle body [*Rosso*, 2007].

Thus, the reflection Moho in Domain 1 is discontinuous with some parts characterized by strong reflectivity, separated by shorter segments where the reflection Moho is barely visible or absent. Apart from a couple of apparent down to the north offsets that are associated with shorter upper mantle reflections that may represent shear zones, the Moho reflection is relatively smooth (Figure 4b, **marker 12**). In the southern part of the northern domain, the reflection Moho has a modest convex downward shape (Figures 4b and 4c).

The upper mantle displays some isolated areas of strong reflectivity in the northern domain (e.g., Figures 4b and 4c, **markers 7 and 8**). These features may represent intramantle shear zones that do not interfere with the Moho itself or may be the expressions of metamorphic transitions or magmatic intrusions (see general discussion and the description of Domain 3).

3.2. The Central Domain (Domain 2; Transition Between the Caledonian and Proterozoic Regimes)

Domain 2 (Figure 4) is characterized by a change in depth to Moho from 22–25 km in the north (290 km, ILP-10) to 35 km in the south. This 10 km jump in crustal thickness coincides geographically with the offshore projection of the Hardangerfjord Shear Zone (HSZ; Figure 4c, **markers 9 and 13**), which is represented by a band of NW dipping reflections that extend from the surface to 15–20 km depth. A diffuse south dipping swarm of reflections is particularly well expressed at the lower crustal level (Figure 4b, **marker 11**). This swarm of reflections can be followed as a thin zone of very distinct, almost continuous reflections below the Moho in line ILP-10 and all the way to the bottom of the lines at 50 km depth (Figures 4b, 4c, and 5a). Thus, this discontinuity is best defined at the levels of the lower crust and Moho, and the zone of reflections is likely to represent a fundamental south dipping shear zone with a normal-sense displacement of several tens of kilometers. Although the lower crust generally is strongly reflective in both lines ILP-10 an ILP-11 (Figure 4), there are zones of reduced reflectivity that create transparent vertical corridors in line ILP-10, as seen, for example, in Figure 4b, **marker 10**).

The upper crust in the Central domain is characterized by relatively good reflectivity (particularly in line ILP-10, indicating a substantial thickness of sedimentary rocks in the hanging walls of the Hardangerfjord Shear Zone and the Øygarden Fault Complexes (Figure 4)). By comparison, ILP-11 shows poor reflectivity in the upper crust, probably due to lack of substantial sediments on basement along this transect. The reflection pattern in ILP-10 defines a subhorizontal sequence down to ~5 km depth (Figure 4c, **marker 4**). These are interpreted as the east dipping sequence of Mesozoic rocks, including Triassic megacycles described by *Steel and Ryseth* [1990]. South dipping reflections in the basement underneath the Mesozoic section (Figure 5b) are likely to represent a wedge of outboard Caledonian allochthons of the type occurring onshore in the hanging wall to the Hardangerfjord Shear Zone [see also *Færseth et al*., 1995]. A tectonic contact against Proterozoic basement to the north is anticipated from onshore correlations, and south dipping reflections are thought to represent this contact. This tectonic contact is correlated with the onshore Sunnhordland detachment of *Norton* [1987]. Reflections along the trend of the northwest dipping Hardangerfjord Shear Zone are also seen in the upper crust of the Central domain (Figure 4b, **marker 9,** and Figure 5b).

The middle crust in Domain 2 is more reflective than the upper crust but is generally of somewhat poorer reflectivity than that of the middle crust as seen, e.g., in the southern domain (see below). The reflections affiliated with the Hardangerfjord Shear Zone become less steep and merge with the other reflections of the middle crust in the Central domain. The footwall of the Hardangerfjord Shear Zone contains abundant discontinuous reflections oriented parallel to the Hardanger Shear Zone at the middle crustal level.

The middle crust of Domain 2 also contains a highly reflective, dome-shaped body, situated in the footwall of the Hardangerfjord Shear Zone (Figure 4b, **marker 11**). The origin of this feature is unknown, but a magmatic origin is not unlikely.

The lower crust of Domain 2 is characterized by the a swarm of southerly dipping reflections cutting up through the Moho and flattening out near the top of the lower crust. Immediately, south of the swarm of reflections, the top of the middle crust, is faint, but it appears to be offset down top to the south at the border toward the Domain 3 (Figure 4c, **marker 13**). In ILP-11, the lower crust appears to be thicker in this position. An interesting difference between ILP-10 and ILP-11 is that while the former portray a single zone of dipping reflections, line ILP-11 shows a more composite structure at the lower crustal level, with a dislocation on each side of marker 11. The apparent vertical displacement of the reflection Moho is of the same order of magnitude (more than 10 km) in the two sections.

The reflection Moho in Domain 2 can be identified closer to the band of dipping reflections in line ILP-11 than in Line ILP-10 (Figures 4b and 4c), perhaps suggesting that the zone of offset is narrower and more steeply dipping in ILP-11. Based on these observations, we suggest that an extensional, southerly dipping crustal-scale shear zone offsets Moho in a down to the south sense by 10 to 13 km and that the shear zone itself is a relatively narrow feature. Based on correlations between lines ILP-1 and ILP-11, it appears that the structure strikes ENE_WSW, i.e., subparallel to the Hardanger Shear Zone.

Intramantle reflections in Domain 2 are completely dominated by the band of southerly dipping reflections that can be followed down to the lower cutoff of the seismic lines at 50 km (Figures 4b, 4c, and 5b). The reflection pattern and the relations to other structural features strongly suggest that the swarm of dipping reflections is a lithospheric-scale shear zone terminating at the level of the middle crust and offsetting the lower crust and Moho by more than 10 km. This structure is termed the **Hardanger Moho Offset (HMO)** in the following.

It is noted that the HMO has a southerly dip, as portrayed in ILP-10 and ILP-11. Although detailed analysis shows that the HSZ can be traced down to the middle crust [*Fossen and Hurich*, 2005], there is no direct connection between the HSZ and the HMO, demonstrating that no hard-link exists between these two structures.

3.3. The Southern Domain (Domain 3; the Neoproterozoic Tectonic Regime)

The upper crust of Domain 3 is partly transparent but also encompasses strongly reflective zones, associated with late Paleozoic-Mesozoic sediments. The middle crust is moderately reflective, whereas the lower crust and the mantle offer the most reflective segments of the entire ILP survey.

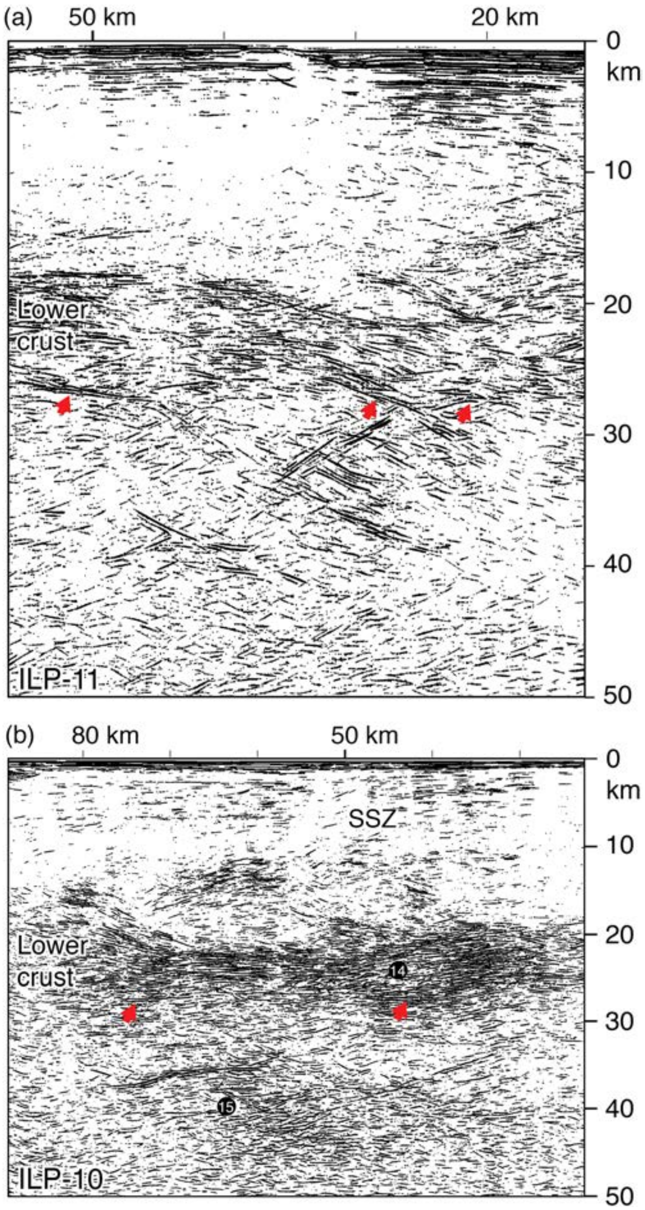

Figure 6. Reflection patterns of the lower crust in the Domain 3. (a) Lower crust/Moho-offset associated with the Hardanger Moho Offset (HMO) as displayed in line ILP-11. (b) Highly reflective lower crust and intramantle bundle of reflections (line ILP-10).

The upper and middle crusts of Domain 3 encompass the extensional Stavanger and Karmøy shear zones, which separates Caledonian Nappes in their hanging walls from lower nappes or basement rocks in their footwalls. Both shear zones are extensional and of Devonian age, with evidence of later brittle reactivation.

The lower crust of the Domain 3 portrays an up to 14 km thick highly reflective band above Moho (Figures 4b and 4c, **markers 6 and 14**). The reflectivity is particularly strong in ILP-10 (Figure 6b). In both lines, the highly reflective lower crust is abruptly terminated in the north by a wide and diffuse low-reflectivity zone and the HMO. The lower crust in the southern domain is delineated by an uneven reflection Moho at its base and a strong very uneven package of reflections at its top. In total, this lower crustal body is approximately 5 km thick. Its uppermost boundary is particularly well expressed south of the surface trace of the HMO, whereas it gets fainter toward the south (Figure 4c, **marker 14,** and Figure 6b). The northernmost part of the body seems to display contrasting geometries; in ILP-11, this body shows an increase in thickness toward the north, whereas in line ILP-10, it is bound by more parallel upper and lower reflections. The upper delineation of the highly reflective lower crustal body is characterized by a very uneven and disrupted surface. Consequently, when seen along strike of the lines, the reflection package of the lower crust in this domain is strongly heterogeneous: it consists of a series of south dipping elements, each separated by a transparent, dipping zone, creating a “train” of overturned structures, resembling contractional large-scale tectonic lenses. However, no distinct reflections resembling faults or shear zones can be identified. Although most pronounced in line ILP-10, the lower crustal highly reflective body is also apparent in line ILP-11 (Figures 4b and 4c). Individual structures as seen on the top of the body (Figure 4c, **marker 14,** and Figure 6b) dip southward and flatten and merge with the core of the lower crustal body, perhaps indicating that the lower crust that have been disrupted and displaced top to the north.

The reflection Moho in the Domain 3 is by a highly variable signature and interrupted by minor offsets (low-angle shear zones?) (Figures 4 and 6a). Here the reflection Moho disrupted along several south dipping zones of reflections (shear zones?), creating apparent reverse offsets of the reflection Moho with vertical displacements in the order of 1 km. Some pronounced discontinuities at the reflection Moho level are seen

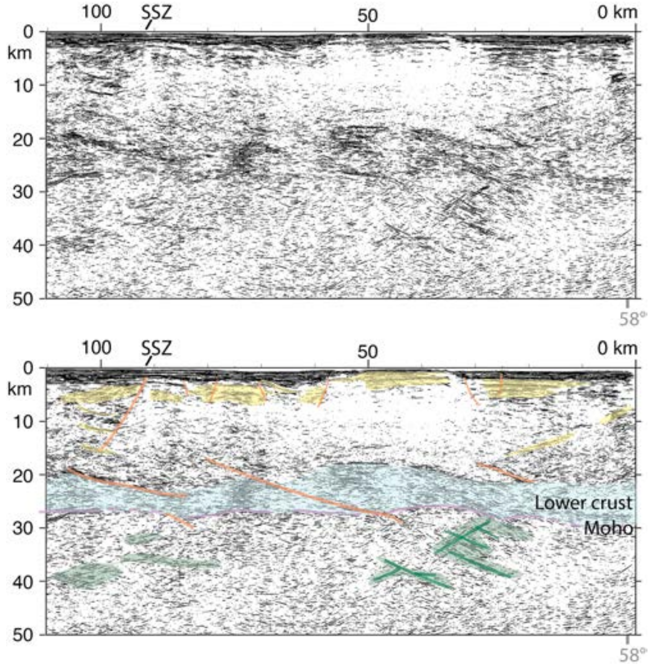

Figure 7. Lower crust in Domain 3. Note south dipping swarms of high reflectivity separated by zones of low reflectivity. Areas of strong reflection are indicated in yellow (upper and middle crusts), blue (lower crust), and green (mantle).

in both lines but are particularly well displayed in line ILP-11 (Figures 7a and 7b). Some of these discontinuities can be interpreted as low-angle shear zones with an apparent top to the north displacement

Also the mantle of the Domain 3 is characterized by an anomalous pattern of reflections compared to the other parts of the study area. Three types of very prominent sub-Moho reflection patterns are seen in Domain 3. A 3–4 km thick band of high reflectivity in the uppermost mantle (Figure 4c, **marker 15**) is bordered upward by a remarkably distinct reflection seen at 35 to 45 km depth. A similar, but much fainter feature is also seen in line ILP-11. The reflection that defines its upper border suggests a strong contrast in velocity and density to the overburden. The highly reflective northern upper border of the feature dips to the north upper part southerly dipping to flat, whereas the southern part, which less reflective, is characterized by southerly dip. In total, this feature may be seen as a lens shaped structure with a N-S axis of more than 60 km. The less pronounced signature as seen in line ILP-11 may indicate that it tapers out toward the east. It is noted that this strong band of reflections terminates abruptly against the diffuse (?shear) zone that separates Domains 1 and 2.

4. Discussion

Detailed interpretation of the lower crust and the upper mantle from deep reflection seismic data is commonly difficult and controversial due to limited seismic resolution and the uncertainty of geological constraints. In the case of the reprocessed ILP-lines reported upon here, some very distinguished and indisputable observations can still be made: (1) As seen in the eastern shoulder of the Viking Graben, the reflection seismic lines clearly display along-strike segments of contrasting seismic reflection characteristics and structural character (northern, central, and southern domains as described above). Such findings were also reported by *Færseth et al.* [1995], who studied the middle crust of the North Sea albeit they proposed a somewhat different definition of domains. (2) The lower crust in the Domain 3 (southern domain) contains zones of south dipping reflections, separated by more seismically transparent zones. (3) Intra-upper-mantle reflections are common in the study area, both as linear reflections and more irregular bundles of reflections. Particularly one of these features, that penetrate far into the lower crust, is seen as a shear zone offsetting the reflection Moho down to the southwest by approximately 10 km. One large, lensoid-shaped and several minor reflective areas are found in the upper mantle.

It is realized that the origin of reflections in the seismic data may be debatable but the consensus in most cases of deformed crystalline terranes is that the reflections originate in macro-scale fabrics enhanced by compositional variation and potentially anisotropy related to preferred crystal orientations. In the case of the Hardanger Shear Zone, reflections are clearly associated with fabric development in the shear zone. Likewise, extension accommodated by the proposed lower crustal shear zones and distributed extension in the lower crust of the Western Gneiss Region most likely resulted in well-developed fabrics that produce seismic reflections.

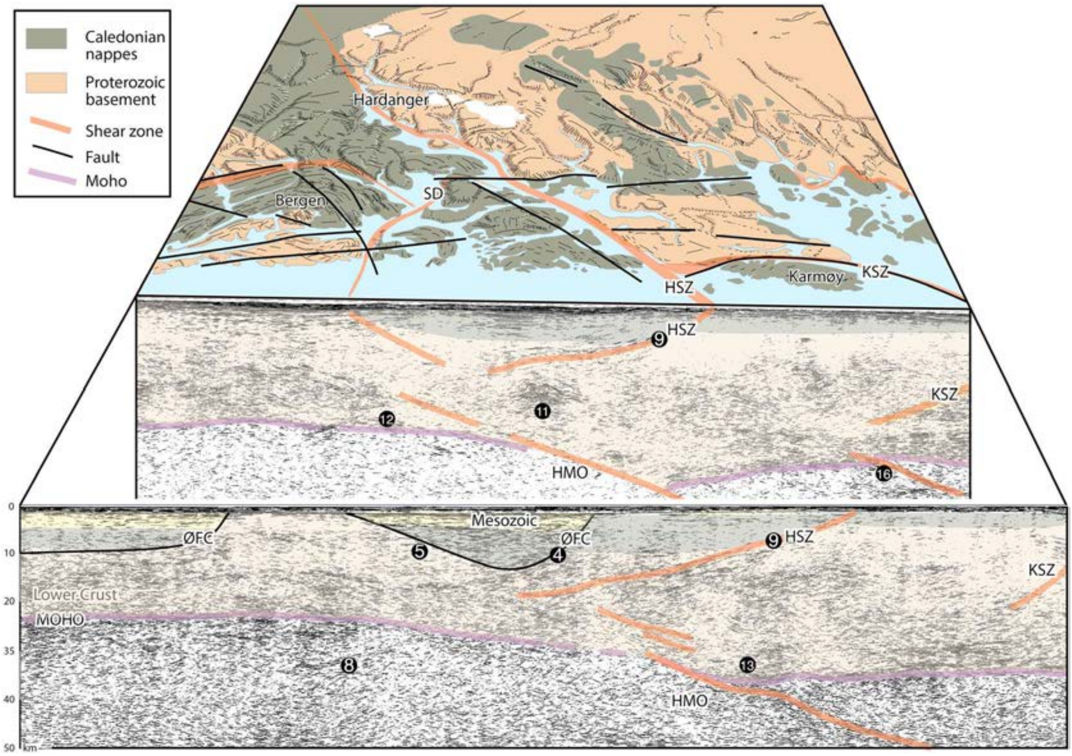

Figure 8. Lines ILP-10 and ILP-11, their relation to the onshore geology, the Øygarden Fault Complex (ØFC), the Hardangerfjord Shear Zone (HSZ), and the Hardanger Moho Offset (HMO) (see also Figure 1). SD = Sunhordland Detachment, KSZ = Karmøy Shear Zone.

Lithospheric-scale segmentation, the structural pattern seen in seismic lines ILP-10 and ILP-11, suggests that segmentation of the coast-parallel profiles are related to the interference of major structural thick-skin features like Nordfjord-Sogn Detachment (NE-SW and NW-SE striking); the Hardangerfjorden, Karmøy, and Stavanger shear zones and related deep structures; and the (N-S striking) Øygarden Fault Zone. This interference of structural elements gives rise to juxtaposition of different basement units and a significant basement relief, in accordance with the distinction of a northern, a central, and a southern domain (Domains 1–3). This segmentation also coincides with the juxtaposition of contrasting structural styles and orogenic terranes, going from thick-skin Caledonian structural terrane in Domain 3 (north) to thin-skin deformation Caledonian deformation and outcropping Neoproterozoic (Sveconorwegian) lithologies in the Domain 3 (south) [see also *Slagstad et al*., 2008, 2011].

The reflective lower crust has previously been assumed from the study of lithospheric architecture in northwest Europe that the middle part of the crust and the mantle beneath extensional basins are generally transparent in reflection seismic data, whereas the lower crust is reflective [*Cheadle et al*., 1987; *McGeary*, 1987; *Blundell*, 1990]. It is also anticipated that the character and structure of the lithosphere and the relief of the reflection Moho obtained during prerifting tectonothermal events may be preserved in favorable cases [*Lucas et al*., 1993; *Juhlin et al*., 1996; *Milkreit and Wu*, 1996; *Németh et al*., 1996; *Simancas et al*., 2013]. A reflective lower crust seems to be typical for many parts of Scandinavia, e.g., along the Central Caledonian Transect of north mid-Norway [*Juhojuntti et al*., 2001] and in the Svecofennian Domain [*BABEL Working Group*, 1990, 1993a, 1993b].

In the study area, the lower crust and the reflection Moho are clearly displayed in wide areas of the study area. The most reflective part of the lower crust is found in the southern domain. Here south dipping segments of high reflectivity are separated by zones of lower reflectivity. Similar structures are known from the Protoproterozoic Trans-Hudson Orogen [*Lucas et al*., 1993] and the Mesoprotrozoic and Neoprotrozoic parts of the Central Indian Suture Zone of the Himalayan Orogen [*Burg et al*., 1994; *Mandal et al*., 2013]. There, the structures are taken as indications of contractional shear, consistent with a strong lower crust

[*Burg et al.*, 2002; *Mandal et al.*, 2013]. Also, *Meissner* [1996] emphasized that contraction structures in the lower crust has a better potential for preservation than do extension structures and cited the Wind River Thrust in Wyoming [*Smithson et al.*, 1979, 1980], the Grenville front in North America [*Green et al.*, 1988; *Milkreit et al.*, 1990], and the Appalachians as examples of this.

The structural features previously recorded in the lower crust and upper mantle of the North Sea are generally extensional. However, the observations on Domain 3 in the present study suggest that contraction structures may be present in deep crustal positions here. In the southern domain, it is natural to associate these structures with the Sveconorwegian Orogeny, where a northerly vergence is proposed (see also sections of *Andersson et al*. [1996] and *Lie and Andersson* [1998]).

Intra-upper-mantle reflection complexes are abundant and well documented from previous studies of deep reflection seismic data in the North Sea [*Beach*, 1986; *Beach et al*., 1987; *Klemperer and White*, 1989; *Klemperer and Hurich*, 1990; *Færseth et al*., 1995; *Odinsen et al*., 2000a], and are also found many places in the present analysis. These types of features occur either as isolated reflection bands in the upper mantle or as structures associated with offsets of the reflection Moho. In several cases, the positions of these structures occur beneath shallower structures. The most striking example of this is the co-location of the HSZ (shallow) and the HMO (deep), but intramantle linear reflection bands are also found beneath for example the Nordfjord-Sogn Detachment. Although a genetic association between the intracrustal structural features and their intramantle counterparts remain to be confirmed, the HSZ-HMO system seems to be related, perhaps to Devonian (post-Caledonian) extension (H. Fossen et al., submitted).

The Domain contains larger, intramantle, reflection complexes. One of these is ~40 km long and 10 km in the vertical dimension. The feature has a dome-shaped geometry (sub-Moho heterogeneities and related packages of reflections may be common [e.g., *Pavlenkova*, 1996; *Rogers and Santosh*, 2004] but frequently fail to be detected sometimes due to suboptimal data processing). *Deemer and Hurich* [1994] demonstrated that layered intrusions as well as granulite facies mineral assemblages may produce strongly reflective units that would be clearly distinguishable from surrounding, nonlayered rocks. In principle, such highly reflective zones may also represent layered eclogite facies assemblages [*Fountain et al*., 1994; *Meissner*, 1996; *Camacho et al*., 2005], and neither of these interpretations for the intramantle reflections can presently be ruled out. A magmatic origin still seems likely, particularly because the study area (southern domain) is situated close to regions of abundant Neoproterozoic intrusions, and it is therefore reasonable to assume that the intra-upper-mantle anomalous reflection packages represent intrusions belonging to this magmatic event. Magmatic intrusions of post-Neoptoterozoic age are also possible interpretations.

5. Conclusions

The present study demonstrates a complex lithospheric architecture of the eastern margin of the Viking Graben that must be taken into consideration in further synthesis and modeling of the study area. Analyzing the interplay between the onshore and offshore structural development of western Norway (Figure 8) has also been very important for the present interpretations.

We particularly emphasize the following observations:

1. The reflection Moho is of variable character going from north to south in the study area. Changes in its character coincide with contrasts in lithospheric reflectivity, configuration, and structural style.
2. The lower crust is generally highly reflective in the study area, with the most conspicuous highly reflective segment being situated to the south (southern domain). The strong reflectivity and structural complexity suggest a strong lower crust, and it is suggested that the highly reflective segment can be preserved from Neoproterozoic orogenic events.
3. The thickness of the crust varies by more than 10 km within the study area. The most significant change in Moho depth occurs beneath the Hardangerfjord Shear Zone Hardanger Moho Offset system. It has been suggested that the Hardangerfjord Shear Zone shear zone may have nucleated in Neoproterozoic times [*Fossen and Hurich*, 2005], but that reactivation of the entire HSZ-HMO system may be younger. Both structures flatten on the midcrustal level, but the structures dip in opposite directions, and are not hard-linked.
4. Highly reflective bodies in the upper mantle are common, most of which are believed to represent shear zones. Some of the shear zones co-insides spatially with shallower structures of regional significance,

perhaps indicating a coupling. More complex bundles of reflections are likely to represent magmatic intrusions. The age of these intrusions can only be speculated upon and the intrusions may be of Neoproterozoic, Caledonian, or post-Caledonian age.

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