Crustal stretching in the Scandinavian Caledonides as revealed by deep seismic data

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ABSTRACT

The normalization of overthickened orogenic crust after a continent-continent collision typically involves several different processes, including erosion, plate divergence, gravity-driven collapse of the orogenic wedge, and viscous flow of the lower crust. As a contribution to this discussion, we here utilize reprocessed deep seismic data to image the Scandinavian part of the major Caledonian continent-continent collision zone where we identify a double set of extensional shear zones: one in the upper to middle crust (Hardangerfjord shear zone) and a major oppositely dipping Moho-offsetting shear zone in the lower crust and upper mantle. The latter shear zone may have a true displacement close to 50 km and appears to offset the Moho vertically by ~10 km, extending downward beyond the 50 km depth limit of the seismic data. While the upper structure offsets the basal Caledonian thrust, the Moho shear zone is more difficult to date. However, they are kinematically consistent and located at the transition zone between thick- and thin-skinned post-collisional tectonics, and we suggest that they may represent a crustal "pinch" or zipper-like structure that separated viscously flowing Caledonian lower crust from cooler rigid basement representative for the rest of the Baltic Shield. Later extension created the North Sea rift, but the general rift axis and the associated rift-related thinning developed in a narrower zone that runs oblique to the Devonian trend, hence the two generations of extension and thinning can be distinguished at the crustal scale.

INTRODUCTION

Continent-continent collision zones go through a progressive increase in crustal thickness, and the zone as a whole becomes gravitationally unstable once the convergent plate motions come to an end or even get replaced by plate divergence. At this stage the upper and middle crust typically involve extensional reactivation of thrusts as well as the formation of new extensional faults and shear zones. The response of the lower crust and upper mantle is more enigmatic. They may be hot and weak enough to flow and distribute strain evenly (McKenzie, 1978; Turcotte and Schubert, 2002), they may develop major shear zones that extend into the mantle (Gibbs, 1987; Wernicke, 1985), or they may be too cool and stiff to deform (the thin-skinned situation). In this work we have reprocessed deep seismic lines that cross the foreland-hinterland transition of the stretched Scandinavian Caledonides. The seismic data support a model where flowing Devonian crust was separated from rigid crust by a transition zone defined by oppositely dipping extensional shear zones.

GEOLOGIC SETTING

The Caledonian orogen in the North Atlantic region (Gee et al., 2008) culminated with the Late Silurian to Early Devonian westward subduction of Baltica beneath the Laurentian margin, during which the leading edge of Baltica locally reached depths on the order of 125 km in southwestern Norway (van Roermund et al., 2002). In this region, the switch from Caledonian convergence to post-collisional divergence is recorded by tectonic fabrics in the Caledonian basal décollement (Fossen, 1992), and dating of micas that grew during the two phases suggests that the switch occurred shortly before 400 Ma (Fossen and Dunlap, 1998).

Extensional reactivation of the low-angle Caledonian basal décollement implies a reversal of the motion of Baltica; i.e., eduction (Duretz et al., 2012). However, this mode of extension transitioned into the formation of hinterland-dipping shear zones, shown as green lines in Figure 1. This system of extensional shear zones extended to the surface, giving rise to Devonian supra-detachment basins, of which remnants are preserved in the hanging wall of the Nordfjord-Sogn detachment (Séranne and Séguret, 1987; Vetti and Fossen, 2012). In this work we will focus on another of these Devonian extensional shear zones, the Hardangerfjord shear zone (HSZ). This upper- to mid-crustal structure displays ~10–15 km of post-Caledonian displacement (Fossen and Hurich, 2005), and is ductile with a brittle overprint primarily represented by the Lærdal-Gjende fault (Andersen et al., 1999).

DATA AND OBSERVATIONS

The rift- and coast-parallel seismic lines that form the key data set in this paper are based on deep (long-offset) reflection seismic data collected in 1988 through the Mobile Search campaign led by the University of Bergen, Norway (ILP-10 and ILP-11) (Klemperer and Hurich, 1990), designed to image the lower crust and upper mantle. The raw data were subjected to post-stack reprocessing (time-migration, coherency filtering, tuning of bandpass filters, and depth conversion) at Memorial University (Newfoundland, Canada) to enhance middle- and lower-crustal reflectivity. Velocity information for migration and depth conversion was derived from co-located wide-angle data, as discussed by Deemer and Hurich (1991). For description and discussion of the rift-perpendicular lines shown in Figure 1 (North Sea Deep Profile 1 [NSDP-1] and NSDP-2), see Christiansson et al. (2000) and Odinsen et al. (2000).

The Crust

The two ILP lines both show a well-stratified reflective lower crust overlain by a more transparent upper crust. The upper crust shows a set of dipping reflections with an orientation and location that fit the offshore extension of the HSZ. This shear zone is a 20°–25° NW–dipping ductile Devonian structure that displays 10–15 km of post-Caledonian displacement that affects the Proterozoic basement as well as overlying Caledonian nappes. The package of dipping reflections that matches the HSZ is also imaged on conventional seismic lines from the area and on two short cross-lines published by Fossen and Hurich (2005), and can be traced downward to the top of the lower crust.

The lower crust shows a coherent reflective pattern that varies in strength along the sections. The fact that syn- to post-collisional igneous activity is nearly unknown in south Norway, and that a strong Caledonian fabric and gneissic layering are observed in crustal rocks in the Western Gneiss Region, suggest that gneissic compositional layering or tectonic fabric is the main cause of acoustic anisotropy along these lines.

Moho and Mantle

The base of the crust is represented by a locally strong reflection that corresponds with the top of a high-velocity (8.1–8.4 m/s) layer iden-

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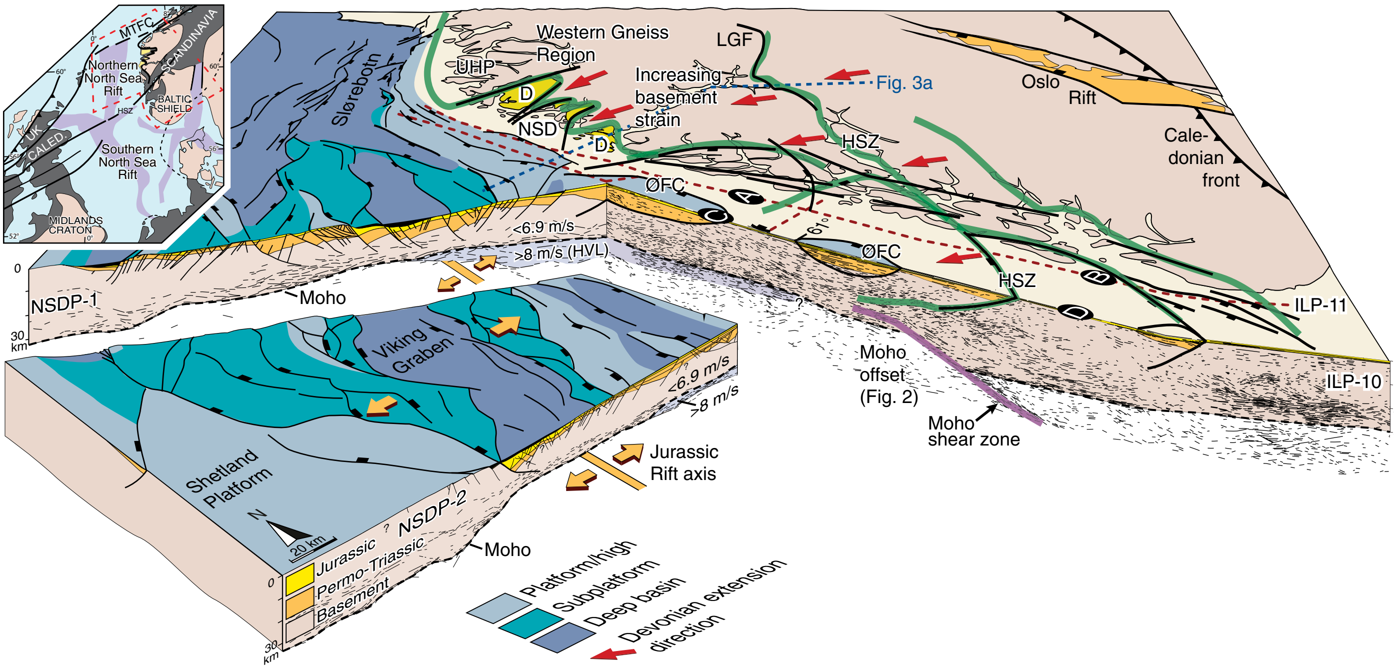

Figure 1. Three-dimensional view of northern North Sea–south Norway area, built around the four deep seismic lines discussed in text (ILP-10, ILP-11, NSDP-1, NSDP-2). Red arrows indicate Devonian extension direction, green lines are major ductile Devonian shear zones, black lines are brittle faults, and orange arrows indicate Permian-Triassic extension direction (rifting). D—Devonian; HSZ—Hardangerfjord shear zone; LGF—Lærdal-Gjende fault; MTFC—Møre-Trøndelag fault complex; NSD—Nordfjord-Sogn detachment; ØFC—Øygarden fault complex; UHP—ultra-high pressure; HVL—high-velocity layer.

tified on the east side of the Viking Graben (HVL in Fig. 1, marked as >8.0 m/s). Christiansson et al. (2000) believed this to be a partially eclogitized body, but we now consider it to be part of the upper mantle for several reasons. (1) It seems unlikely to have a sufficiently high percentage of eclogite in such a large body of continental basement gneisses; mafic pods and bodies that in part transformed into eclogite during the Caledonian orogeny amount to no more than ~2% of the Western Gneiss Region basement (Hacker et al., 2010). (2) Including the high-velocity layer makes the crust unreasonably thick, considering the relatively high amount of Permian-Triassic extension seen in the upper crust. (3) While density information is not available for this high-velocity body, its high velocities (8.1–8.4 m/s), confirmed by Rosso (2007), are typical mantle velocities. Hence, by definition (Steinhart, 1967), this high-velocity zone is below the seismic Moho.

Moho Offset

The main focus of this contribution is the significant Moho offset that appears across the location of the HSZ. Our Moho interpretation of ILP-11 (closest to the mainland) shows a south-to-north jump from 37 to 26 km, while the corresponding jump in ILP-10 is from 35 to 22 km (Fig. 2). This ~10 km vertical offset occurs across a partly reflective zone dipping ~13° to the south, which we interpret as a normal-sense (extensional) shear zone with true displacement close to 50 km (Fig. 1). Correlation of the two lines suggests that the shear zone that offsets the Moho strikes parallel to the HSZ, but with opposite dip, with a true dip somewhere between 15° and 20° to the southeast. More conservative interpretations, where the high-velocity layer is included in the crust, also yield significant Moho offsets. Hence we have a situation where the upper extensional shear zone (HSZ) is mirrored by a Moho-offsetting shear zone in the upper mantle–lower crust, and where the two shear zones strike parallel to the strike of the Caledonian orogen and oblique to the north-south–trending North Sea rift (Fig. 2).

DISCUSSION

The Moho Offset

The seismic expression of the Moho and its down-to-the-south offset is quite clear from the seismic lines, and any reasonable alternative interpretation would only reduce the vertical offset by a few kilometers. Gravity modeling along the lines is inherently difficult because of the effect of the line-parallel Øygarden fault complex (Fig. 1) and basement anoma-

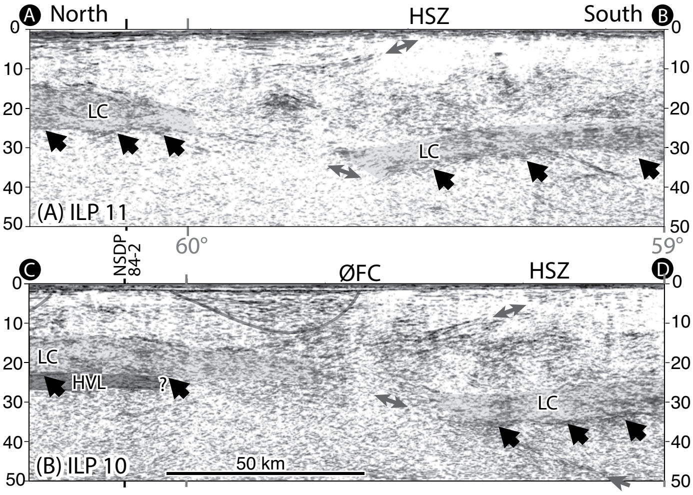

Figure 2. Close-up of parts of seismic sections ILP-10 and ILP-11. Black arrows point at reflective Moho; smaller gray arrows indicate shear zone locations. Lower crust (LC) and high-velocity layer (HVL) are indicated. See Figure 1 for locations and abbreviations. Vertical scale (in km) equals horizontal scale.

lies related to Caledonian allochthons. Furthermore, differences between topography and mantle relief in the region suggest that crustal and upper mantle heterogeneities exist (Maupin et al., 2013; Stratford et al., 2009). The high-velocity layer underlying the seismogenic Moho (Fig. 1), whose southward extent is not well constrained, is an example of such a heterogeneity that complicates isostatic modeling. Nevertheless, the simple gravity model presented by Hurich and Kristoffersen (1988) shows the Moho to step up to the north by ~5 km across the HSZ.

The dipping reflections cannot represent remnants of a subducted Caledonian slab, such as those discussed by Abramovitz and Thybo (2000) in the southern North Sea, because the Caledonian subduction in the northern North Sea area was oppositely directed and located farther northwest (e.g., Hacker et al., 2010). A Proterozoic subduction zone is also unlikely, as the normal Moho offset is at odds with a subduction zone model. The fact that the HSZ affects the Caledonian nappes shows that its present offset accumulated during post-thrusting crustal extension. We do not have similar constraints on the complementary mantle-offsetting structure, and it is possible that it involves Proterozoic offset, including Neoproterozoic crustal stretching (Andersen et al., 2012). Nevertheless, its colocation, parallelism, and kinematic consistency with the HSZ make it likely that the two shear zones acted simultaneously during Devonian crustal stretching.

Crustal Thinning

The crustal thinning associated with the HSZ and the Moho shear zone is supported by data from deep seismic refraction profiles (Magnus Rex project led by Copenhagen University, Denmark) onshore southern Norway, which suggest a change from a flat Moho at 36–38 km depth southeast of the HSZ to a westward-shallowing Moho starting at the location of the HSZ (Stratford et al., 2009) (Fig. 3A). The resolution of these data is too low to test whether or not a discrete Moho offset exists, as suggested by the seismic lines, but the data clearly demonstrate that the location of the HSZ marks the transition from a horizontal crustal base (Moho) to northwestward-thinning crust. The transition from a flat Moho in central Norway to a dipping Moho (northwestward-thinning crust) across the HSZ coincides with the transition from thin-skinned to thick-skinned tectonics: the Baltican basement is almost unaffected by Caledonian strain southeast of the HSZ, whereas the same basement shows evidence of variable and locally very strong ductile late- or post-Caledonian strain to the northwest (Milnes et al., 1988, 1997), as shown in Figure 3A. The basement strain increases northwestward from the HSZ, and in the northwestern part of the area shown in Figure 1, the basement (Western Gneiss Region) is strongly sheared and metamorphosed, with local evidence of partial melting (Gordon et al., 2013; Labrousse et al., 2011). This strain gradient relates to the weakening effect caused by the general increase in basement temperatures to the northwest during the Caledonian subduction-eduction history (Fauconnier et al., 2014).

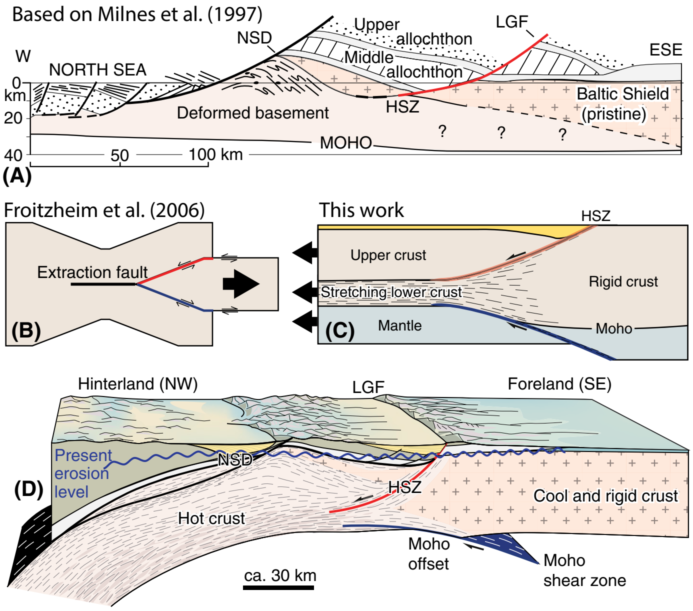

Figure 3. Models used to explain the viscous-rigid crust transition. A: Milnes et al.'s (1997) Sognefjord transect through the Caledonides, showing their interpretation of deformed basement. Moho is adjusted according to Stratford et al. (2009). NSD—Nordfjord-Sogn detachment; LGF—Lærdal-Gjende fault; HSZ—Hardangerfjord shear zone. B: Extraction fault model of Froitzheim et al. (2006). C: Kinematic interpretation of transition zone described in this work. D: Schematic sketch of setting during Devonian extension in south Norway Caledonides. HSZ and the complementary Moho shear zone are shown.

Paired Shear Zone Model

The crustal temperature would have been at its highest, and hence the crustal viscosity at its lowest, at the onset of eduction and extension rather than during subduction, simply because of the time it takes to heat the subducted slab of continental crust. Accordingly, most ductile structures in the Western Gneiss Region reflect Devonian (ca. 400 Ma) extensional top-to-the (north)west shearing (Milnes et al., 1997) (Fig. 3A), implying that the crust to the northwest of the HSZ was mobile during Devonian eduction and exhumation. In contrast, Proterozoic lower crustal to subcrustal structures have been shown to be preserved underneath the Baltic Shield outside of the Caledonian orogenic belt (Artemieva and Meissner, 2012), suggesting stability in this region since the Precambrian. We suggest that the HSZ and the Moho shear zone together form a paired extensional structure that accommodated this difference in basement behavior. Hence we suggest that this double shear zone structure may represent a Devonian extension structure, possibly with a pre-Caledonian history.

Technically the structure bears some similarities to the class of structures described by Froitzheim et al. (2006) (Fig. 3B). However, the extension fault in their more discrete or brittle model is here replaced by a plastic (flowing) lower crust (Figs. 3C and 3D) that may flow by sub-simple shear. Hence, the lower crust would be expected to stretch in a northwesterly direction as the upper plate stretches more heterogeneously with the formation of extensional shear zones and faults, some of which are portrayed in Figure 1.

Effect of Rifting

Post-Devonian crustal thinning occurred along the North Sea rift, particularly during a Permian-Triassic and a Late Jurassic rift phase (Færseth et al., 1995; Heeremans and Faleide, 2004). The thinning effect of these two rift phases on the crust is portrayed by the two cross-sections NSDP-1 and NSDP-2 in Figure 1, where the thickness of the crystalline crust is reduced from >20 km at the intersection with ILP-10 to <10 km along the rift axis. This rift-related thinning is also indirectly reflected by ILP-10 and ILP-11, as the Moho is found to be somewhat deeper on the landward line (ILP-11) than on the line closer to the rift (ILP-10). However, the main effect of rift-related tectonics is seen west of the ILP lines.

CONCLUDING REMARKS

In conclusion, we have found evidence for an upper mantle–lower crustal shear zone that offsets the Moho vertically by ~10 km and is kinematically compatible with a middle- to upper-crustal shear zone (HSZ). We suggest a model where these structures were simultaneously active in the Devonian, soon after the change from a convergent Caledonian to a divergent post-Caledonian regime. In this model, the structure formed in the transition zone from cool and rigid Baltica crust in the southwest to relatively hot and partly flowing crust involved in Caledonian subduction and eduction/exhumation in the northwest. If the crust northwest of the HSZ was stretching and thinning while the crust southeast of this zone was left intact, this may help to explain why the present crustal thickness reaches its maximum east of the HSZ (Ebbing et al., 2012) rather than in the original Caledonian root zone in the (ultra-)high-pressure northwestern part of the Western Gneiss Region. Hence, the present data suggest a wide zone of Devonian post-Caledonian crustal flow that gave way to North Sea rifting and associated crustal thinning in a narrower and more north-south–trending zone.

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