1. Nature of Palaeozoic extension in Lofoten, north Norwegian Continental Shelf: insights from 3-D seismic analysis of a Cordilleran-style metamorphic core complex

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Abstract

Analyses of 3-D seismic data reveal that pre-Triassic basins are present underneath the Mesozoic North Træna Basin (Lofoten Margin, Norway). These are linked to a Cordilleran-style metamorphic core complex that developed in Palaeozoic times, including rotated fault blocks with hanging wall ‘growth’ wedges, bounded by listric faults detaching onto a sub-horizontal detachment. Based on similarity in age, structural style and transport direction we propose a kinematic link with a Permian mylonitic detachment documented onshore. This study presents the first offshore evidence for Palaeozoic detachment faulting, elucidating the mechanisms behind the long-lived exhumation history of the Lofoten basement.

Introduction

Metamorphic core complexes (MCC) are associated with exhumation and juxtaposition of high-grade metamorphic basement rocks against lower-grade upper crustal rocks across low-angle detachments, and were first described in the North American Cordilleras (e.g. Lister & Davis 1989). Gneiss-cored exhumation complexes of Palaeozoic age, related to collapse and unroofing of the Caledonian orogen, are well documented in the Western Gneiss Region of south Norway (e.g. Andersen et al. 1991). However, although the exhumed basement and low-angle detachment are commonly preserved, the classical MCC geometries of the upper

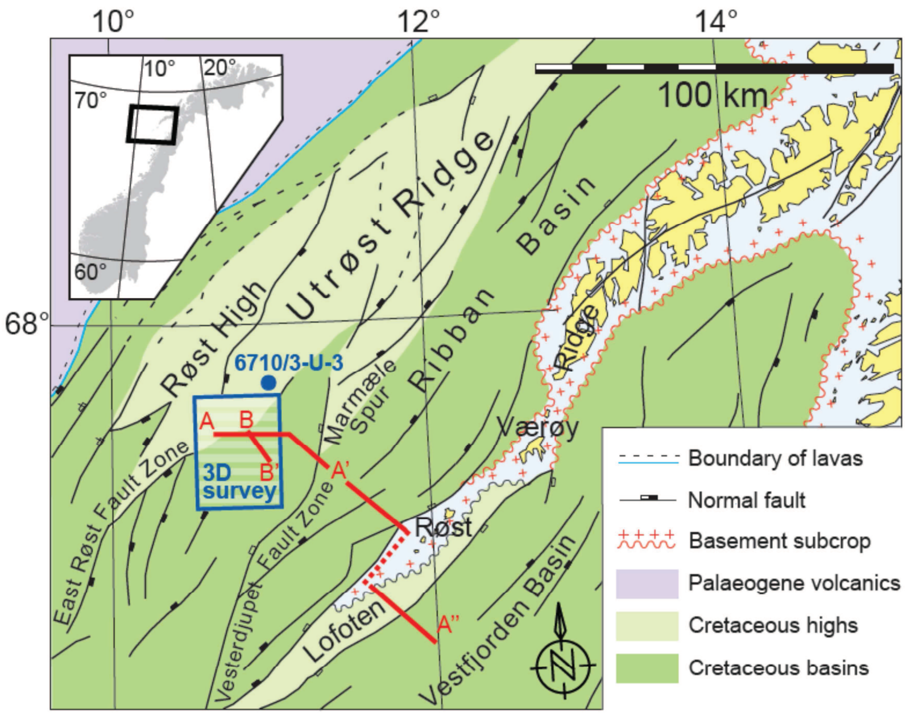

Figure 1. *Structural element map of the Lofoten segment of the Norwegian continental margin. The 3-D seismic survey and well 6710/3-U-3 are indicated in blue; the locations of the sections of Figures 2 and 4 are shown in red. Modified after Blystad et al. (1995).*

plate are rarely seen, either due to lack of preservation or lack of exposure (Osmundsen et al. 2005).

In this study, a reprocessed 3-D seismic dataset (Fig. 1) that offers imaging of the pre-Triassic succession with unprecedented clarity is used to elucidate the nature of Palaeozoic extension and exhumation in the Lofoten margin. We describe a probable-Permian MCC, which features classical geometries such as transport of severely rotated fault blocks over a low-angle detachment. The fault blocks are associated with hanging-wall basins containing syn-tectonic ‘growth’ strata. Although not directly age-constrained, these strata are situated c. 0-1500 ms below a well-tied near base-Triassic reflection. Herein we present i) the documentation, ii) a simple reconstruction, and iii) a model for the formation of the MCC in Permian times.

Previous onshore workers have suggested that the Lofoten Ridge (LR) forms part of a Permian MCC (Hames & Andresen 1996; Olesen et al. 2002; Steltenpohl et al. 2004), based on i) the presence of lower crustal rocks at surface, ii) an age-constrained Permian, sub-horizontal, mylonitic detachment that crops out on the islands of Røst and Værøy and iii) a shallow Moho underneath the LR. This study underlines that the previously-suggested MCC is regionally extensive (Steltenpohl et al. 2011), and provides the first offshore evidence for basement denudation related to probable-Permian-aged low-angle detachment faulting.

Tectonostratigraphic framework of the Lofoten margin

The partly submerged LR represents a c. 200 km long, NNE-trending regional basement high, comprising lower crustal, mangeritic rocks (Hames & Andresen 1996), which is flanked to the east and west by rift basins of Cretaceous and older age (Fig. 1). The geology of Northern Norway is to a large extent dominated by the imprint of the Caledonian orogeny, which culminated during Iapetus closure and the penultimate collision of Baltica and Laurentia in Late Silurian to Early Devonian times (Gee & Sturt 1985). The contractional phase of the Caledonian orogeny in Scandinavia was superseded by a stage of syn- to post-orogenic collapse in Devonian times (Andersen et al. 1991; Fossen 2000). Extension in the Western Gneiss Region (WGR) of southwest Norway is manifested by the presence of large-scale supradetachment basins filled with Devonian clastics, but no deposits of this age have been reported in the Lofoten. Furthermore, while most of the exhumation and cooling of allochthonous rocks through ~350 °C took place prior to c. 390 Ma in the southern WGR (Berry et al. 1995), the unroofing of similar structural levels in the Lofoten area occurred in several stages over c. 150 m.y., lasting well into the Permian (Hames & Andresen 1996). Investigating the nature of Permian extension offshore to the southwest of the Lofoten archipelago is, therefore, important to understanding the regional exhumation history.

The evolution of the Lofoten margin since the Palaeozoic is characterized by an extended rift phase that led to continental break-up in the Eocene (Mosar et al. 2002) and post-break-up uplift in Oligocene-Miocene times (Doré et al. 1999). The oldest sedimentary rocks drilled west of the Lofoten archipelago are of earliest Triassic age and resemble alluvial fan deposits directly overlying crystalline basement, similar to the mangeritic bedrock of the Lofoten islands (Hansen et al. 1992). The possible presence of a Palaeozoic succession below the Mesozoic strata in the North Træna basin has been recognized previously. However, the sedimentary nature and Palaeozoic age of such a succession is disputed; it is treated as a sedimentary wedge by some authors (Hansen et al. 1992; Tsikalas et al. 2001; Bergh et al. 2007), while others refer to it as basement (Færseth 2012). In this paper we provide evidence for the sedimentary nature of these pre-Triassic reflections as well as the relation to Palaeozoic exhumation of the Lofoten margin.

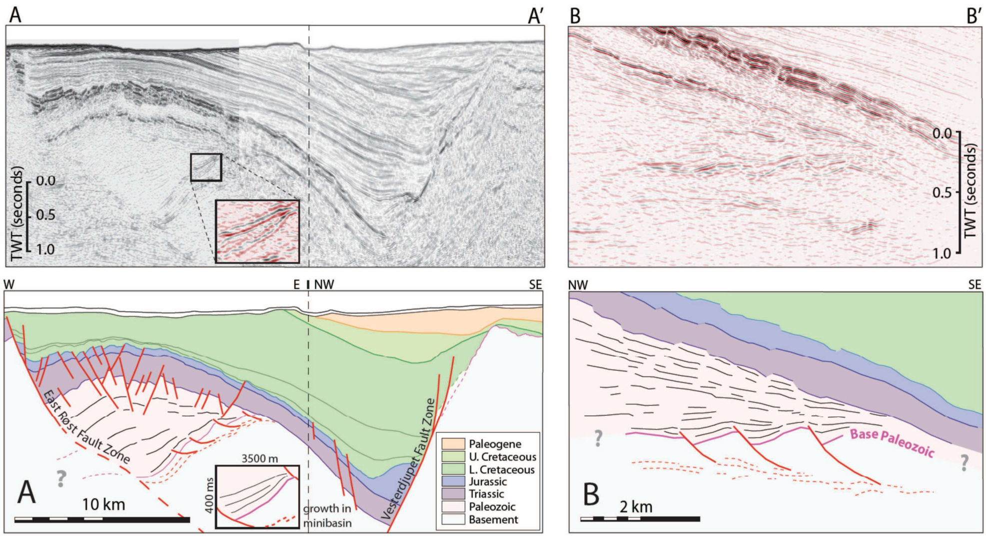

Figure 2. *Geoseismic sections across the North Træna Basin. A-A' shows a key section across the basin with the Palaeozoic megasequence visible below the Mesozoic. B-B' shows a more detailed image of the Palaeozoic wedge; note the rotated fault blocks separated by listric faults detaching onto a deeper bundle of reflections, representing a basal detachment. When flattened at top Triassic (see Fig. 3c), the detachment zone would dip to the northwest.*

Evidence for Palaeozoic extension in the (proto-) North Træna basin

Our database comprises a reprocessed three-dimensional, pre-stack time-migrated seismic reflection survey that was acquired in 1996 over the northern part of the North Træna basin, c. 3 km south of where the Triassic-basement contact was drilled (IKU shallow core 6710/3-U-3; Fig. 1). It has a line spacing of 12.5 m and a vertical resolution of c. 25 Hz within the stratigraphic interval of interest. Stratigraphic control is provided by shallow core 6710/3-U-3 (Hansen et al. 1992) and tied to the 3-D survey via 2-D seismic reflection lines (seismic-well tie is available in the data repository). Within the shallow core, the base Triassic event is also the sediment/basement interface; the seismic-well tie shows how both events separate towards the south to give way to the pre-Triassic wedge.

This Palaeozoic megasequence consists of a westward-expanding wedge of semi-transparent seismic character; tracing the wedge eastward, it becomes progressively more condensed as reflectors coalesce and the wedge thins to almost nothing before being truncated at the erosional base Triassic event (Fig. 2a). To the west, it thickens to c. 1500 milliseconds two-way travel time (ms); here, the wedge is bounded by the East Røst Fault Zone (ERFZ). The dipslope of this Palaeozoic graben forms the deepest continuous reflector here and, as based on a tie to well 6710/3-U-3, represents the sediment-basement interface at the base of the wedge. It should be noted that the interpretation of the seismic image away from this well-tie is not unambiguous and that the possibility of even older Palaeozoic strata being present below this deepest continuous reflector cannot be ruled out.

The dipslope of the Palaeozoic graben is itself disrupted by a series of imbricate, rotated, extensional fault blocks, separated by east-dipping listric faults (Fig. 2b). The top basement reflector is mappable within a relatively small area of approximately 20 km2, revealing the N-S to NNE-SSW strike of the 1-2 km wide fault blocks; the faults are about 10 km long (Fig. 2; a structure map is provided in the data repository). Wedges of ‘growth’ strata occupy the accommodation space (c. 200 ms;

Figs 2b and 3) that was generated as the fault blocks rotated. These expand by a factor two over a distance of 1 km, clearly too much to be explained by differential compaction.

The listric faults sole out on a discontinuous bundle of reflections that occurs a few 100 ms below the sediment/basement reflector. This bundle signifies a detachment zone. In a strike-normal section, this detachment zone and reflections within the lower part of the supra-basement sediments broadly parallel one another (Fig. 2b). This means that by the time the fault blocks moved with respect to one another, the detachment zone was a subhorizontal feature a few hundred meters below surface. By flattening on the base Triassic event, thereby removing the imprint of Mesozoic rifting and Cenozoic uplift, it becomes evident that the top-to-the-east detachment zone became west-dipping ('warped') by latest Palaeozoic time (Fig. 3).

Discussion and conclusions

With the arrival of improved seismic it can now be confidently concluded that a distinct sedimentary megasequence is present below the base Triassic event (see Fig. 2a) as tied to shallow core 6710/3-U-3. The drilled Triassic sediments are assigned a Griesbachian age (Hansen et al. 1992); this is the earliest stage of the Triassic spanning only 1 m.y. following the peak of the Permian-Triassic extinction event. The strata that make up the underlying megasequence must therefore indeed belong to the Palaeozoic; we tentatively assign a Permian age following the relatively late exhumation of the Lofoten Margin. An older age (Devonian / Carboniferous) for these sediments cannot be discarded, however; Carboniferous strata have been documented in the SW Barents Sea and a Devonian age was obtained for structures related to the Eidsfjord Shear Zone (Steltenpohl et al. 2011). The oldest sediments belonging to this megasequence were laid down as a syn-tectonic unit in the mini basins that formed as a response to rotation of the small fault blocks (Figs 2b and 3a). These sediments thus record activity of the listric faults and therefore the first eastward movement over the detachment. This period of localized deposition was followed by more widespread deposition in response to the development of a large

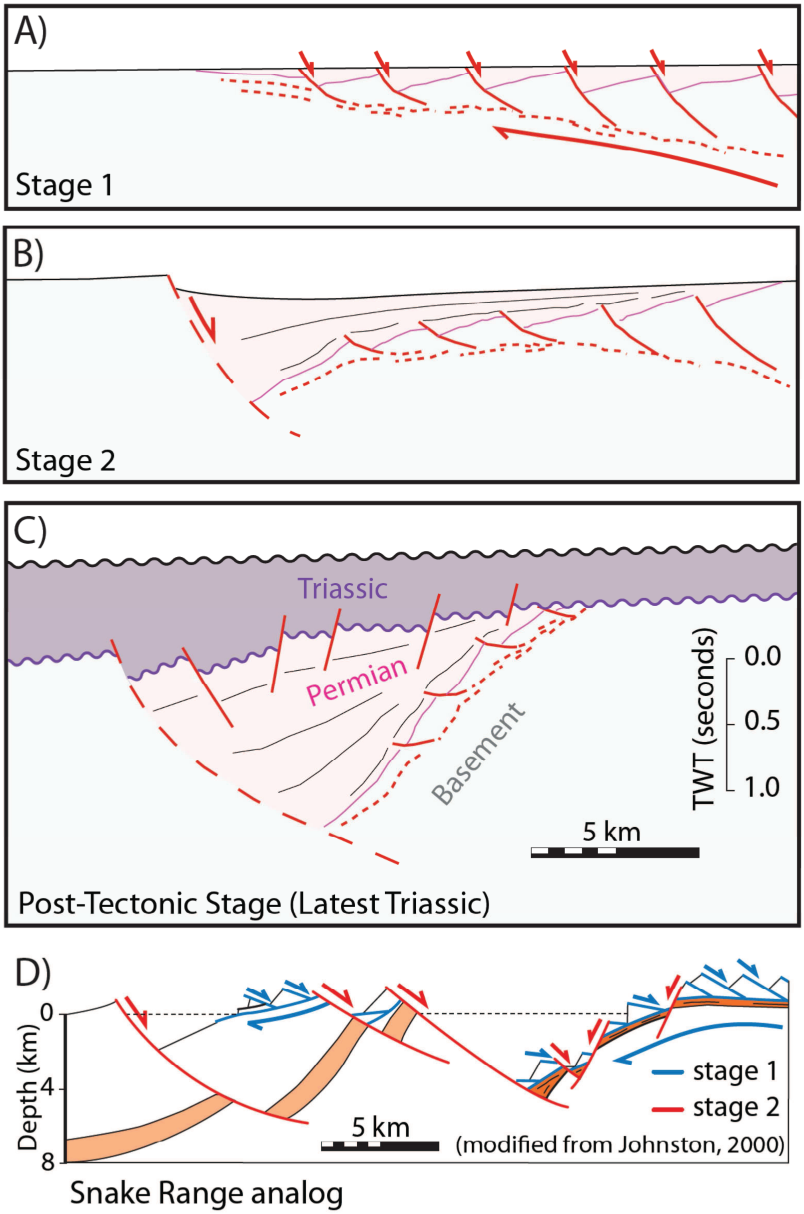

Figure 3. *Conceptual reconstruction of the Palaeozoic succession of geoseismic section A-A' from Fig. 2. a) Early stage of fault block rotation. b) Sedimentation changes from isolated depocentres to more widespread deposition in response to the development of listric faults that do not sole out on the detachment. c) The situation at the end of the Triassic: late Permian erosion has removed parts of the metamorphic core; Triassic rift faults preferentially nucleate over the Permian basin. d) Structural analog; initial transport of small fault blocks over a crustal detachment zone, followed by the development of syn- and antithetic listric faults and large depocentres 'upstream'.*

fault to the west (possibly the proto-ERFZ), which gave rise to the wedge-shaped configuration of the megasequence observed today (Figs 2a and 3b). More continuous Permian reflections belonging to the larger wedge (Fig. 2b) indicate that the smaller listric faults were less active (Fig. 3b); moreover, the development of the larger halfgraben resulted in the downthrowing of the detachment, making it dip to the west (Fig. 3b & 3c).

Older Palaeozoic sediments may be present below the reflector currently referred to as basement. It could therefore be speculated that the fault blocks (Fig. 2b) moved over a ductile medium within such an older sedimentary sequence. Evaporitic deposits that are good condidates for facilitating subhorizontal transport are known from Palaeozoic basins in the SW Barents Sea (Faleide et al. 2008).

The novel interpretation of the pre-Triassic root to the North Træna basin presented here closely resembles that of the area between the crustal culmination and the breakaway fault of a Cordilleran-style metamorphic core complex (MCC), with i) transport of listric fault blocks over a sub-horizontal basal detachment and ii) ‘upstream’ development of a relatively large depocentre, resulting in iii) down-warping of the detachment (Wernicke 1985; Lister & Davis 1989). The development of the up-dip breakaway zone of the Snake Range MCC as interpreted by Johnston (2000) bears a striking resemblance to the Permian features seen in the North Træna basin. Initial small-scale listric faulting over the main detachment zone (Fig. 3d) is followed by the formation of larger listric faults that are dipping steeper and do not sole into the main detachment.

Given its (inferred) age, structural style and inferred movement sense, it is likely that the detachment zone proposed herein connects to the ductile detachment zone previously described onshore Røst and Værøy, which are exposed parts of the LR (Fig. 1). The latter structure led other workers to strengthen the case for the existence of an MCC here (Steltenpohl et al. 2004), after it had first been suggested by Coker et al. (1995) and Hames & Andresen (1996). A direct link between their onshore and our offshore work would make the detachment a significant basement detachment, stretching c. 50 km E-W from the Vestfjorden Basin to the Røst High. This supports the notion that the MCC is of potential regional importance and responsible for both the exhumation of the crystalline basement in the Lofoten area (Steltenpohl et al. 2011) and the formation of the probable-Permian proto-North Træna Basin (Fig. 4). Crustal-scale simple shear related to MCC development would typically produce an asymmetric structural template with mantle upwelling closer to the down-dip end of the detachment zone (Wernicke 1985). This is in good agreement with the fact that the Moho anomaly culminates underneath the Lofoten ridge (Mjelde et al. 1996; Faleide et al. 2008), away from the breakaway zone in the North Træna basin and towards the downdip end of the broadly-east-dipping detachment zone (Fig. 4). If the detachment zone of the proto-North Træna basin is in fact formed along an older salt layer as speculated before, this asymmetrical template would have included a ramping up of the detachment in westerly direction, thereby forming a connection between the crystalline ductile shear zone in the east and a shallower stratigraphic detachment horizon in the west.

Based on the strike (N-S to NNE-SSW) of the listric faults that sole out on the Permian detachment zone in the North Træna basin, the tectonic transport direction is E to ESE. This differs some 45 degrees from the transport direction of mylonitic shear zones at Røst/Værøy (top-to-the-ENE/NE; Steltenpohl et al. 2004). The trend of ductile shear (obtained from strain indicators such as elongation lineations, folds and/or porphyroclasts) on MCCs are known to vary up to several tens of degrees within distances of a few tens of kilometers with respect to the overall extension vector (e.g. Bargnesi et al. 2013). It is likely that neither the transport direction of fault blocks we observe in the North Træna basin, nor that of the mylonitic shear of Røst/Værøy is fully representative of the overall extension direction which is believed to have been E-W in Permian times (Doré et al. 1999; Mosar et al. 2002).

Other observations and previous work can be explained in conjunction with this model and thus offer further support. Firstly, brittle NE-SW trending normal faults of Permian age are described further to the NE in the Lofoten archipelago (Klein et al. 1999), in the hanging wall of the detachment zone of Røst/Værøy (Steltenpohl et al.

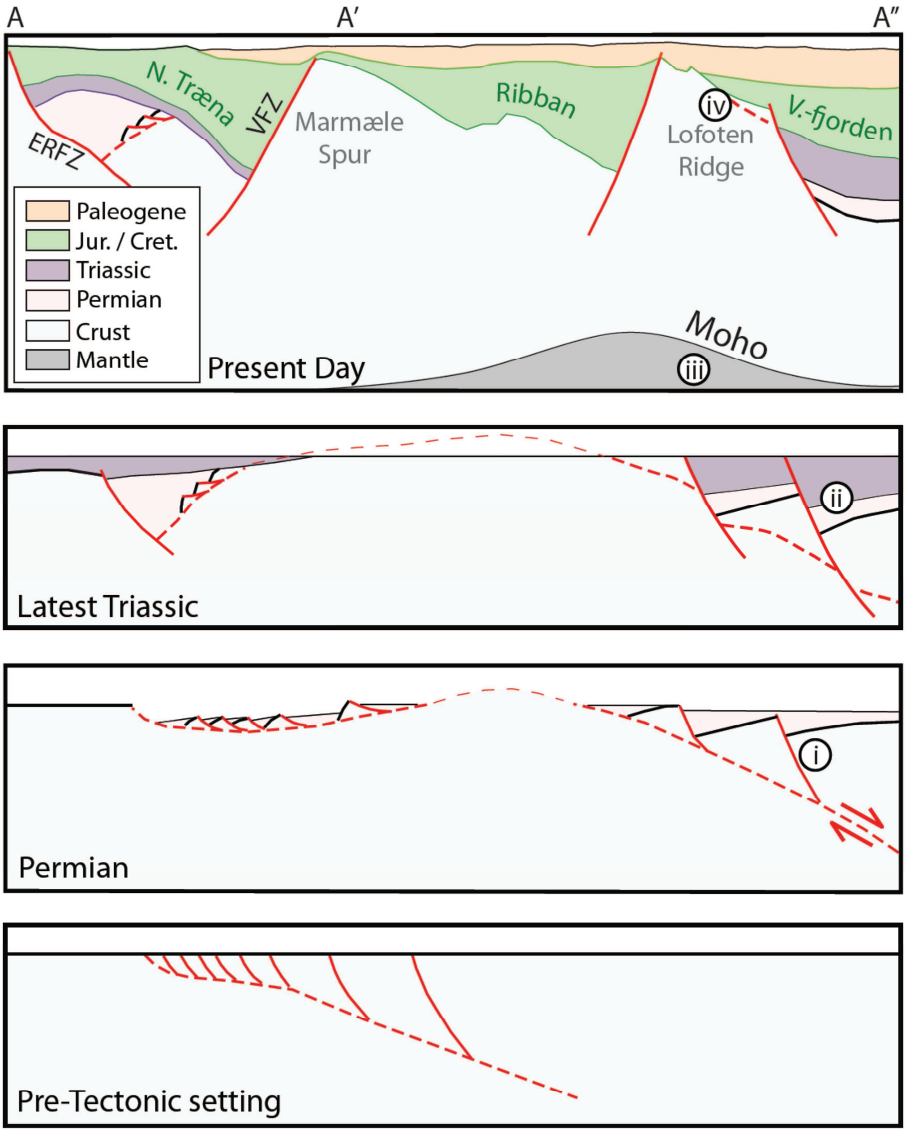

Figure 4. *Proposed model for the late Palaeozoic development of a Cordilleran-style metamorphic core complex and the younger overprint of the Cretaceous rift. The left hand side of the sections is based on observations and interpretations described in this paper (see Fig. 3). The right hand side is more hypothetical, based on a combination of observations done by other workers: i) Permian brittle faulting (Klein et al. 1999); ii) Palaeozoic sediments at the base of the Vestfjorden basin (e.g. Færseth 2012); iii) a shallow Moho (Mjelde et al. 1996); iv) a top-to-the-northeast ductile detachment fault over the Lofoten Ridge (Steltenpohl et al. 2004).*

2004). Such synthetic normal faults typically develop in the upper plate, down-stream of the main core complex where the detachment zone ramps down to lower crustal levels (Wernicke 1985). Secondly, the suspected presence of Palaeozoic sediments in the Vestfjorden basin (Mjelde et al. 1996; Færseth 2012) suggests such upper plate, synthetic normal faults are associated with syn-tectonic sedimentation and occur not just onshore Lofoten, but over a large area east of the LR. Thirdly, the southern part of the Ribban basin (Fig. 1) was not flooded before the Kimmeridgian (Hansen et al. 1992), which is significantly later than neighboring basins; the buoyant, denudated crust appears to have produced a long-lived relative high.

In summary, based on the observations and interpretations presented herein and in combination with findings of previous workers, we propose that the evidence for an MCC documented onshore in SW Lofoten (Hames & Andresen 1996; Steltenpohl et al. 2004) forms part of a much larger, asymmetric structure that facilitated crustal extension and exhumation in Palaeozoic, probably Permian, times. In addition to a shallow Moho, lower crustal rocks at surface and an onshore detachment fault documented before, we recognize a breakaway zone at the base of the North Træna basin. Moreover, we suggest that the main metamorphic window developed where the southern Ribban basin is located now and the suspected Palaeozoic lower part of the Vestfjorden basin formed in response to synthetic normal faults that link up with the downdip end of the detachment (Fig. 4).

Regional Implications

The findings of this study shed light on the exhumation history of lower crustal rocks in the Lofoten margin, the timing and mechanisms of which differ from that of the WGR of south Norway. In the latter region,post-Caledonian exhumation of lower crustal rocks was rapid and largely accomplished by early Middle Devonian times (Dunlap & Fossen 1998), due to crustal-scale extensional collapse and formation of large supradetachment basins. In the Lofoten region on the other hand, post-Caledonian exhumation lasted well into the Permian (Hames & Andresen 1996). This study elucidates the nature of this longer-lived exhumation, providing the first offshore evidence for the development of a Cordilleran-style metamorphic core complex in the Lofoten Margin, which was probably the chief driving mechanism for tectonic unroofing in Permian times. Moreover, there is a striking difference in the size and structural style of the relatively small upper plate basins described herein, compared to that of the scoop-shaped orogenic collapse basins of the southern WGR.

Acknowledgements

We thank Norske Shell for funding and data access. Permission to publish the 2-D data was granted by TGS; the 3-D data by Norske Shell & PL219 partners.

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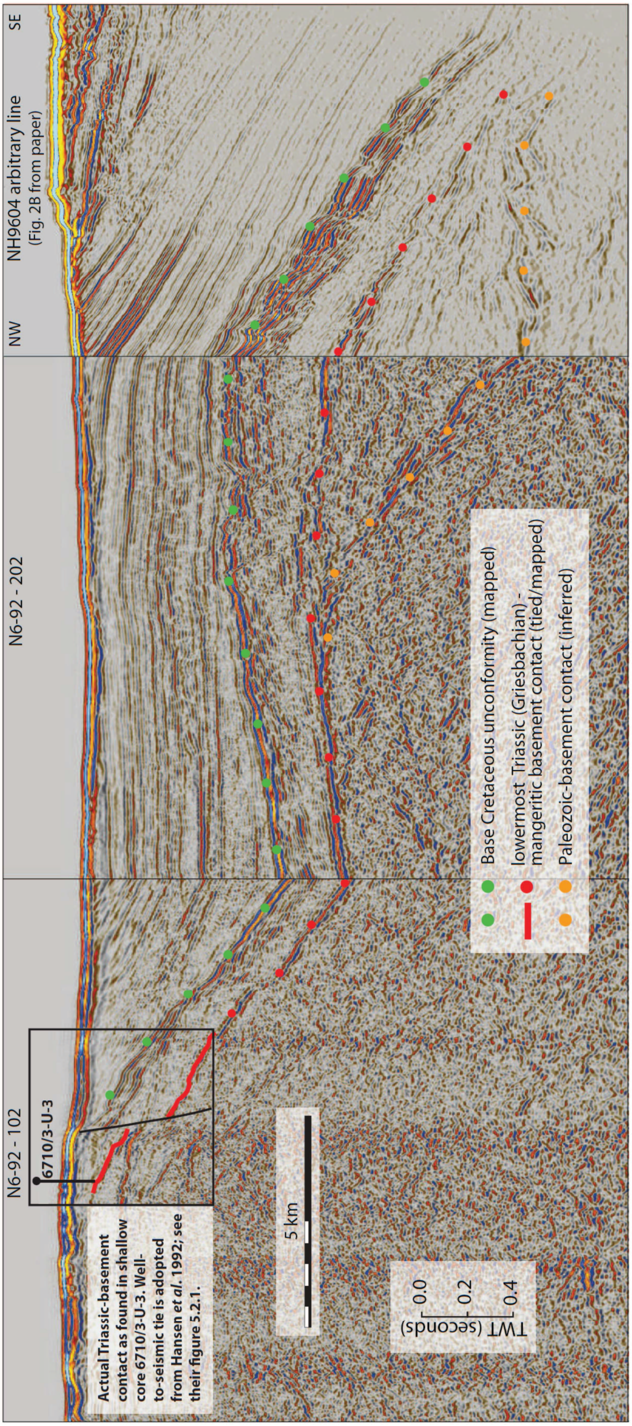

Supplementary Figure. *A composite seismic line providing a tie between shallow core 6710/3-U-3, that drilled through the base Triassic, and section B-B' of Fig. 2.*