Repeated inversion and collapse in the Late Cretaceous–Cenozoic northern Vøring Basin, offshore Norway

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ABSTRACT: The Norwegian Atlantic margin, although frequently described as passive, has seen several significant and highly variable deformation events prior to and after early Cenozoic break-up. This chronology is strongly exemplified in the northern Vøring Basin, where deformation resulted in significant vertical motions, including deep erosion and sediment reworking.

Post-break-up compressional deformation is well documented in the NE Atlantic margins, and is represented in the north Vøring Basin by the Vema and Nagflår domes. A prominent Maastrichtian–Paleocene pre-break-up phase of compression inverted the northern prolongation of the latest Turonian Vrigid Syncline. This syncline was the fairway for the approximately 1 km-thick Santonian–Campanian Nise Formation sandstone, shed from NE Greenland and/or the western Barents Sea margin. The inversion focused on the Vrigid Syncline axis, forming an anticline here referred to as the Vema–Nyk Anticline. The anticline may have been a major trap but was breached by erosion prior to collapse due to Late Paleocene extension. The remnant eastern half of the anticline is the Nyk High. The associated flanking syncline, the Någrind Syncline, also remains preserved. The collapsed side of the anticline is the Hel Graben, which itself was inverted in the Middle Miocene time forming the Nagflår and Vema domes.

More speculatively, the development of the Vrigid Syncline and its bounding structural highs, the Gjallar Ridge and Utgard High, may also represent folds, marking the onset of compressional buckling in the mid-Norwegian–NE Greenland rift system.

The repeated compressional deformation, as well as the extensional collapse, was focused on the area subjected to Early Cretaceous hyperextension. Compressional buckling under relatively low stress levels is proposed to have been due to significant lithosphere weakening caused by the hyperextension, whereby both high attenuation of the crystalline crust and serpentinization of the upper mantle contribute to the weakening. The Late Cenozoic compression post-dated the hyperextension by approximately 110 Ma, which suggests that the weakening is long-lived and that lithosphere has not been strengthened significantly through time.

INTRODUCTION

The area of study lies in the northern Vøring Basin and is part of a Cretaceous–Cenozoic basin system along the NE Atlantic passive margin (e.g. Doré et al. 1999). Structural features in the mid-Norwegian rifted margin (Fig. 1) were named by Blystad et al. (1995).

The mid-Norwegian margin has a long history of episodic rifting, spanning between the Carboniferous and Early Eocene break-up, a duration of approximately 250 Ma. During this long period the extensional stress field rotated significantly, resulting in oblique overprinting of older by younger rifts events (Fig. 2). This is spectacularly displayed by the Early Cretaceous rift that ‘beheaded’ the Late Jurassic rift system (e.g. Lundin & Doré 1997; Doré et al. 1999; Roberts et al. 1999), and by the oblique line of Paleocene rifting and Early Eocene break-up v. the trend of the Cretaceous rift system. As a consequence of the oblique break-up, the hyperextended Early Cretaceous basin chain that once spanned from the West Orphan Basin to the Bjørnøya Basin (Lundin & Doré 2011) is today fragmented into abandoned hyperextended basin elements on conjugate North and NE Atlantic margins.

A suite of mid- to Late Cenozoic compressional features within the NE Atlantic rifted margins, most prominent between the northern Vøring Basin and the northern Rockall Trough, has
been well documented in the literature (e.g., Johnson et al. 2005; Doré et al. 2008; Tuitt et al. 2010). A less well-documented suite of broad folds representing Late Cretaceous compressional shortening has been described in the Vøring Basin (Brekke 2000; Lundin & Doré 2011). Both sets of structures are predominantly located within the fragmented Early Cretaceous basin elements, and a causal relationship with lithospheric weakening due to hyperextension has been proposed (Lundin & Doré 2011).

In this paper, we show how the complex structure of the northern Vøring Basin was influenced by Early Cretaceous hyperextension, setting the stage for multiphase inversion before and after break-up, and how the same area was further imprinted by collapse immediately prior to continental separation.

Our usage of the term ‘hyperextension’ refers to a situation whereby the crust has been sufficiently thinned by extension to cause coupling between the lower and upper crust (Pérez-Gussinyé & Reston 2001; Sutra & Manatschal 2012), in turn permitting faults to penetrate the entire crust and, thereby, hydrate the upper mantle.

**STRUCTURAL FEATURES OF THE NORTH VORING BASIN**

The Vigrid Syncline is a latest Turonian (Brekke et al. 2001) to Paleocene sub-basin in the outer Voring Basin, bounded by the Gjallar Ridge highs to the west, the Utgard High and Fles Fault Zone to the east, and the Rym Fault Zone to the north (Figs 2 & 3). The Någrind Syncline is a Maastrichtian–Paleocene sub-basin bounded to the north by the Bivrost Lineament, to the east by the Utgard High and to the west by the Nyk High. The Nyk High is a truncated fault block that has been interpreted as an eroded footwall to the more enigmatic Hel Graben (e.g. Lundin & Doré 1997; Walker et al. 1997; Ren et al. 2003). All of these authors have assumed that these features were formed by extension of approximately Paleocene age – an episode that heralded Early Eocene break-up and spreading in the adjacent North Atlantic.

The southern boundary to Hel Graben is overprinted by a north-trending anticline, the Vema Dome (Fig 4), which is interpreted to have formed by Middle Miocene compression (e.g. Lundin & Doré 2002; Doré et al. 2008). In this paper, we show that the Vema Dome first rose in Late Maastrichtian–Late Paleocene time (Figs 5 and 6), collapsed in Paleocene time (Figs 7 and 8) and became domed into its current shape in Middle Miocene time (Figs 5 and 6). The sedimentary fill of the Hel Graben was inverted to form the Naglfar Dome (Fig. 8), which is loosely constrained to be a Middle Miocene inversion structure. The south and SW boundaries to Hel Graben are defined by the Rym Fault Zone, which here is considered to be a flexure or faulted flexure. The NW side of Hel Graben is defined by the Vøring Escarpment, constituting the boundary against the Vøring Marginal High. The escarpment has been interpreted to mark a palaeo-coastline in the inner basalt flows manifested as a sharp cliff line (e.g. Planke et al. 1999) but is also a faulted structural break (Brekke 2000). The marginal high remains an enigmatic feature and is generally assumed to be highly intruded transitional crust covered by Late Paleocene plateau basalts associated with break-up (Skogseid & Eldholm 1988).
Repeated inversion and collapse

The Vigrid Syncline spans the Voring Basin from the Gjallar Ridge in the west to the Fles Fault Complex in the east. Flexure of the Vigrid Syncline was initiated in Late Turonian time (Brekke et al. 2001). The Late Turonian–Paleocene succession onlaps westwards against the eastern flank of the Gjallar Ridge, in places to a single point of pinch-out. The western side of the Gjallar Ridge is marked by numerous fault blocks, bounded by west-throwing normal faults which have been interpreted to be of Late Cretaceous–Paleocene age (Lundin & Doré 1997; Ren et al. 2003; Gernigon et al. 2004). We return to the age of the Gjallar Ridge faulting in the Discussion.

LATE CRETACEOUS INVERSION

The mid-Norwegian margin (Fig. 1) contains a thick succession of Cretaceous strata, which to date generally has been interpreted as a post-rift succession to Late Jurassic–Early Cretaceous rifting (e.g. Doré et al. 1999). The Early Cretaceous Voring Basin was reshaped into broad folds in Cenomanian–Turonian time (Brekke 2000; Brekke et al. 2001; Lundin & Doré 2011). Apart from the sources mentioned earlier, this reshaping of the basin in the early Late Cretaceous has been little remarked upon in the literature, where it is tacitly assumed that most of the Cretaceous was represented by passive subsidence and basin infill. However, like Brekke (2000), we point out that the general fold-like geometry of major structures such as the Någrind Syncline (Fig. 9a), the Vigrid Syncline (Fig. 9b) and its bounding anticlines suggest regional (albeit mild) compression. Notably, the succession below the syncline is represented by parallel-bedded strata (Bjornsnæs et al. 1997) with a relatively uniform thickness. Thus, the syncline is not a thermal response to the considerably older Early Cretaceous hyperextension but marks a distinct structural reshaping of the basin. Even the use of the ‘syncline’ nomenclature (Blystad et al. 1995) probably represents an unconscious acknowledgement that the local geometries do not fit a standard extensional pattern. Stratal patterns, such as the onlap of Cenomanian–Paleocene reflectors on to the eastern flank of the Gjallar Ridge (e.g. Lundin & Doré 1997; Ren et al. 2003; Gernigon et al. 2004), support deformation of this age, specifically the rise of the Gjallar Ridge as a bounding anticline of the Vigrid Syncline. Similar evidence for Late Cretaceous deformation is observed at the Utrost Ridge in the outer Lofoten margin. Seismic data reveal onlap of Late Cretaceous strata against the eastern side of the Utrost Ridge (e.g. profile C–C’; Blystad et al. 1995) and the timing is constrained to the Late Cenomanian by IKU borehole 6711/04 U01 (Hansen et al. 1992). Originally, Brekke (2000) interpreted the timing of the onset of the Vigrid Syncline to the Cenomanian, but later (Brekke et al. 2001) revised this to latest Turonian. The discrepancy between this latest Turonian date on the NW flank of the Vigrid Syncline and the Cenomanian date from the IKU borehole may relate to dating uncertainty or could indicate regional variability in onset of the deformation.

The Vigrid Syncline resembles basins formed by lithospheric folding (Clentringh & Buvor 2010). Folding of the basin started approximately 40–60 Ma after the Early Cretaceous hyperextension. The wavelength of the Vigrid Syncline fold is of the order of 80 km. The Rås and Træn basins east of the Utgard High–Fles Fault Complex probably represent another synclinal fold, with the Utgard High and Fles Fault Complex marking the intervening and subsequently collapsed anticline.

The Någrind Syncline can be viewed as the eastern remnant of a wider inverted syncline (palaeo-Vigrid Syncline) that initially spanned from the Utgard High to the western side of Hel Graben. This development is illustrated by a transect (Fig. 9a) between the Gjallar Ridge (6704/12-1), Vema Dome (6706/11-1), Nyk High (6707/10-1) and Utgard High (6605/7-2). This section and seismic data reveal that the Santonian–Early Campanian Nise Formation, a sequence of clean deep-water sandstones more than 1000 m thick (in the former syncline axis) (Kittilsen et al. 1999) characterized by a distinctive ‘stripy’ seismic response, was deposited in an unstructured saucer-shaped basin. Based on the isochore thickness of the Nise Formation and on seismic facies relationships, the axis of a palaeo-Vigrid Syncline extended approximately through the Vema Dome–Nyk High area. There is a general westwards thickening of the Nise Formation, from the Utgard High through the Någrind Syncline to the Nyk High. The Nise Formation and older sequences are folded in the Någrind Syncline and are truncated along the Nyk High fault system (Fig. 7). By implication, deformation forming both the Någrind Syncline and the Vema–Nyk uplift post-date Nise Formation deposition.

Based on heavy mineral and zircon analyses (e.g. Morton & Grant 1998; Morton et al. 2005), and analysis of regional unconformities (e.g. Hamann et al. 2005; Tsikalas et al. 2005), the Nise Formation’s provenance lay in NE Greenland. The offshore Danmarkshavn Ridge, which was deeply eroded in the Late
Cretaceous, is a strong candidate for this provenance. However, a 100 Ma zircon population in the Nise Formation (Morton et al. 2005) cannot easily be tied to NE Greenland but could stem from magmatism in the Svalbard–northern Barents Sea–Amerasia Basin (so-called High Arctic LIP) (e.g. Maher 2001; Shipilov & Karyakin 2011). The Svalbard archipelago is also characterized by a major Late Cretaceous erosional unconformity (e.g. Steel & Worsley 1984; Maher 2001). The influx of voluminous clean sands to the Vøring Basin took place during a period of globally high sea level (Haq et al. 1988) and is suggestive of active tectonics. We infer that the Nise Formation deep-water turbidites were deposited south-southeastwards from NE Greenland and the NW Barents Sea into a gentle palaeo-Vigrid Syncline that spanned the Vøring Basin from north to south. The southern part of the palaeo-syncline is still intact and is represented by the Vigrid Syncline, while the northern part was split by uplift of the Vema–Nyk Anticline.

The Vema–Nyk Anticline is an informal name that we use to indicate the latest Cretaceous uplift that occurred in this area. In a later section, we show that this rise was domal in nature, began in the Maastrichtian and continued into the Paleocene. A Maastrichtian isochore map also suggests Maastrictian onset for the rise of the Vema–Nyk Anticline and the folding of the Någrind Syncline (Fig. 10). This deformation is considered a clear compressional episode that preceded break-up.

**PALEOCENE PRE-BREAK-UP FAULTING**

Pre-break-up extension, beginning in the latest Cretaceous but mainly of Paleocene age, and major marginal magmatism of mainly Paleocene–Early Eocene age have been well documented in the literature (e.g. Doré et al. 1999; Brekke 2000; Skogseid et al. 2000; Ren et al. 2003). In the northern Voring Basin, normal faulting of this age has been documented on the Nyk and Utgard Highs, and thin-skinned faulting has been described in detail on the Gjallar Ridge (Ren et al. 2003). According to the latter authors, the extensional activity was protracted and took place from 85 to 55 Ma; that is, essentially spanning the Campanian–Paleocene interval. Such a long period of crustal extension spanning a considerable portion of the Late Cretaceous appears at odds with the idea of mild regional
Repeated inversion and collapse

Compression causing the inversion of the Vigrid Syncline. However, lines presented by Ren et al. (2003) suggest to us that the pre-Paleocene faulting was limited in scope, perhaps representing or including gravitational accommodation on the bounding anticlines as the Vigrid Syncline inverted and subsided. Some expansion against these faults is in places observed between Ren et al.’s interpreted Campanian reflectors. However, most significantly, all of the reflectors assigned to the Campanian and Maastrichtian are, themselves, strongly offset by the normal faulting. The faults are truncated abruptly at the Top Cretaceous, which in this area is an erosional surface overlain by thin Paleocene sediments, usually Upper Paleocene. These observations suggest that the principal phase of normal faulting occurred in either the latest Cretaceous or, more probably, in the Paleocene.

Strikingly, the most intense pre-break-up faulting occurs on the anticlinal crests – the Nyk High, the Utgard High, the Gjallar Ridge and the Utrøst Ridge – thus suggesting that the Late Cretaceous anticlines were unstable and provided a locus for later (mainly Paleocene) extension.

EVLOLUTION OF THE NYK HIGH, HEL GRABEN AND VEMA DOME

The Hel Graben was defined seismically by Skogseid & Eldholm (1989) and later named by Blystad et al. (1995), who pointed out that the thick basin fill was of disputed age, ranging from Campanian to Paleocene. The larger Hel Graben area, including the bordering Nyk High, Vema Dome and Rym Fault Zone structures (Fig. 1), has several enigmatic features that require explanation. These include: (1) the pre-collapse Vema–Nyk Anticline; (2) the collapsed western flank of the anticline into Hel Graben; and (3) renewed Middle Miocene doming of the Vema and Naglfar domes (e.g. Lundin & Doré 2002; Doré et al. 2008). Northwards-increasing peneplanation of the Nyk High (Lundin & Doré 2002, their fig. 10) is in all likelihood another expression of Middle Miocene compression.

While the structural evolution of the palaeo-Vema Dome is comparatively well understood thanks to three-dimensional (3D) seismic coverage and wells 6706/11-1 (Vema Dome) and 6707/10-1 (Nyk High), the development of the Hel Graben remains less well understood. In particular, structural geometries of strata in the Hel Graben, the hanging wall to the Nyk High, are unusual.

The Naglfar Dome (Fig. 1) is the only mid-Cenozoic dome on the mid-Norwegian margin with a present-day pronounced bathymetric expression, possibly indicating late movement but, more probably, a function of Neogene sediment starvation. Like the Vema Dome, the Naglfar Dome is interpreted to have been inverted in Middle Miocene time (Doré et al. 2008). The Hvitveis (6706/6-1) exploration well on the Naglfar Dome in Hel Graben was targeted on a ‘stripy’ seismic succession, interpreted based on reflective character to be the Santonian–Early Campanian Nise Formation. However, a seismic tie into the Hel Graben is very difficult, if even possible. Initial reports by the operator (Esso) suggested that the Nise Formation had been penetrated but biostratigraphic dating by the Norwegian Petroleum Directorate reveals that the well did not penetrate deeper than the Selandian (Williams & Magnus 2010). Owing to the considerable difference in biostratigraphical dating, the Hvitveis well has been redated
Fig 5. Shaded relief maps, with isochore maps draped over the Campanian structure map of Figure 4. Colours indicate isochore thickness in relationship to the palaeo-Vema Dome structure. (a) Maastrichtian isochore demonstrating erosional truncation above the palaeo-Vema Dome; (b) Paleocene isochore illustrating collapse into Hel Graben; (c) Neogene isochore illustrating inversion of the current dome.
Repeated inversion and collapse

Fig. 6. East–west seismic profile across the Vema Dome and Nyk High revealing the main structural stages. (Top) Present day, revealing the Middle Miocene Vema Dome. (Middle) Flattened on top of Oligocene, revealing Paleocene–Eocene infill after Late Paleocene collapse along the Nyk High extensional system. (Bottom) Flattened on the Base Cenozoic unconformity, revealing the palaeo-Vema Dome.
numerous times, more than any other Norwegian well. However, a Paleocene age at total depth (TD) now appears undisputable (Williams & Magnus 2013). IKU shallow borehole 6707/04-U-01 on the Naglfar Dome encountered Lower Eocene cemented ash beds lying unconformably beneath the Upper Pliocene–Pleistocene sequence (Mørk et al. 2001). This corroborates our proposal that the Hel Graben collapsed in Paleocene time, and contains an unusually thick Paleocene succession.

The evolution of the area is illustrated by a series of maps and profiles. Structural mapping at Campanian level (top Nise Formation) in the Vema–Nyk area illustrates the present-day structure (Fig. 4). Draping of isopachs on the structure map demonstrates the structural–stratigraphic development through time. The Maastrichtian isopach draped over the Campanian structure map (Fig. 5a) brings out the location of the latest Cretaceous palaeo-Vema Dome (the southern end of the Vema–Nyk Anticline). Draping by the Paleocene isochore (Fig. 5b) shows infill in the collapsed Hel Graben, and draping of the Neogene isopach (Fig. 5c) reveals the location of the present-day Vema Dome, approximately 9 km further west of the palaeo-dome.

The evolution is also well expressed by an east–west seismic profile across the Vema Dome–Nyk High (Fig. 6). Flattening at the Base Cenozoic unconformity brings out the Late Cretaceous palaeo-Vema Dome (Fig. 6b), and flattening at the near top Oligocene level reveals Paleogene infill above the Base Cenozoic unconformity (Fig. 6c), while the present-day profile reveals the Middle Miocene inversion.

The collapse of the western flank of the Vema–Nyk Anticline is illustrated by a NW–SE profile across the Nyk High and SE Hel Graben (Fig. 7). A most revealing aspect of this profile is that the unconformity can be followed down the degraded Nyk High fault scarp to at least 4.5 s TWT. Note how the strata in Hel Graben lap on upwards against the unconformity.
Repeated inversion and collapse

Fig. 9. (a) Geoseismic profile between the Gjallar Ridge (6704/12-1), Vema Dome (6706/11-1), Nyk High (6707/10-1) and Utgard High (6607/5-2) wells. The section illustrates that the Santonian–Early Campanian Nise Formation (stippled) was deposited in an unstructured saucer-shaped basin, which subsequently was inverted by the rise of the Vema–Nyk Anticline, also forming the Någrind Syncline. Note that the western half of the section lies south of the Hel Graben and, therefore, was unaffected by its collapse structuring. (b) The Turonian–Maastrichtian Vigrid Syncline (left half of profile), the Utgard High and the Rås Basin. For the location see Figure 1. After Lundin & Doré (2011).

DISCUSSION

The northern mid-Norwegian margin experienced a series of significant Late Cretaceous and Cenozoic deformational events, spatially overprinting one another. Following Early Cretaceous hyperextension (Lundin & Doré 2011), the northern part of the basin chain became subject to Late Cretaceous compression. The Voring Basin deformation is not isolated, and can be regarded as a southerly outpost of the more significant contractional structuring observed around the incipient Barents Sea plate boundary to the north. These movements include the principal phase in the development of the Senja Ridge and Veslemøy High in the SW Barents Sea, both structural highs resulting from Late Cretaceous inversion and shale diapirism with a suspected strike-slip component. (Riis et al. 1986; Gabrielsen et al. 1990). Further north,
Svalbard was emergent through the entire Late Cretaceous, with erosion apparently increasing northwards across the archipelago (Stein & Antcliffe 1984). This curious anomaly at a time of major Mesozoic marine flooding is likely to further represent constriction at the incipient plate boundary. Prior to Early Eocene break-up, Svalbard lay adjacent to the Wandell Sea Basin of NE Greenland, where small isolated sedimentary basins underwent folding and thrusting in the Late Cretaceous and Early Paleocene (Manby & Lyberis 2000; Håkansson & Schack-Pedersen 2001). These compressional movements along the Barents–Greenland margin are usually viewed as resulting from strike-slip, a precursor to the development of a dextral shear margin in the western Barents Sea in the Paleogene (e.g. Håkansson & Schack-Pedersen 2001), although others regard the compression as orthogonal to the incipient plate boundary (e.g. Manby & Lyberis 2000).

Maastrichtian–Paleocene inversion of part of the Vigrid Syncline is documented earlier. This event inverted the Santonian–Campanian Nise sandstone fairway in the axis of the Vigrid Syncline. The Nise Formation can be linked to a provenance off NE Greenland, such as the Dammarkshan graben, and to the NW Barents Sea margin, both of which underwent uplift in the Late Cretaceous. Erosion to form this voluminous turbidite deposit, at a time of extremely high eustatic sea level, is indicative of active tectonics. Hence, onset of inversion within the Cretaceous basin chain can be inferred back to the Santonian–Campanian at least. As noted, the Vigrid Syncline is not a classic thermal sag response to preceding rifting and it is tempting to suggest that this large fold also may have a compressional origin. However, the difficulty in proposing a compressional origin for this feature lies in the biostratigraphically dated succession in the Gjallar Ridge.

Three main observations have led to the interpretation of Late Cretaceous extension on the west flank of the Gjallar Ridge (e.g. Lundin & Doré 1997; Ren et al. 2003, Gernigon et al. 2003). These are: (1) onlapping/pinch-out of the post-Late Turonian strata in the Vigrid Syncline against the east flank of the Gjallar Ridge; (2) clear extensional fault blocks on the west flank of the Gjallar Ridge, offsetting a ‘stripy’ seismic succession; and (3) Upper Cretaceous-age dating of strata in the 6704/12-1 well on the Gjallar Ridge. A cause–effect relationship is often implied between the Upper Cretaceous–Paleocene onlap against the east flank of the Gjallar Ridge and the extension on the west side.

Regardless of model, the ‘stripy’ succession in the fault blocks along the west flank of the Gjallar Ridge has been correlated on seismic character alone. This is arguably analogous to the earlier work in the Hel Graben correlating the Nise Sandstone with the ‘stripy’ succession (e.g. Ren et al. 2003), which was later shown by the 6706/6-1 well to be of Paleocene age. Hence, we raise the possibility that the ‘stripy’ succession in the Gjallar Ridge fault blocks may similarly be Paleocene.

It is unclear whether the Late Cretaceous inversion was continuous or episodic. Onlap relationships of Turonian–Paleocene strata in the Vigrid Syncline against the eastern flank of the Gjallar Ridge (e.g. Lundin & Doré 1997; Ren et al. 2003) reveal that the syncline succession locally coalesces to a single point. This single-point onlap suggests that the Gjallar Ridge was actively rising during deposition of the Turonian–Paleocene succession in the Vigrid Syncline. Notably, the Maastrichtian–Paleocene sedimentary fill of the Vigrid Syncline overlapped in time with the rise of the Vema–Nyk Antcline, and the associated development of the Utrøst Ridge (Fig. 3). Therefore, a conceivable scenario is: (a) compressional buckling of the Voring Basin in Late Turonian time with the development of the Vigrid Syncline; (b) continued inversion of the Dammarkshan Ridge off NE Greenland (and off the greater Svalbard area) during Santonian–Campanian; and (c) rise of the Vema–Nyk Antcline in Maastrichtian–Paleocene time.

Thus, a picture is emerging of semi-continuous inversion of a formerly hyperextended rift basin, with the focus of inversion shifting within the basin.

We speculate that the Gjallar Ridge was predominantly extended in the Paleocene, and that extension along the western flank of the Gjallar Ridge linked with Paleocene extension along the Nyk High via the Rym Fault Zone relay structure. The style of deformation changes from a faulted flexure along the Rym Fault Zone, to a clearly faulted hinge in the Vema Dome area, to the highly degraded collapsed scarp along the central and northern Nyk High (and further north along the western side of the Utrøst Ridge). This change of deformation probably represents progressively more collapse to the north and could relate to changes associated with trapdoor-style downfaulting of Hel Graben. It is clear from the line of break-up (Fig. 2) that the Paleocene extension cut across the pre-existing Cretaceous basin. Not surprisingly, the suggested distribution of Paleocene extension mimics the line of break-up.

The dramatic collapse along the Nyk High and the Rym Fault Zone resembles caldera collapse geometries (Branney, 1995). Indeed, it has previously been proposed that Hel Graben represents a large Paleocene caldera (Lundin et al. 2002). If formed by a caldera eruption, the size of the Hel Graben would be indicative of ashflow caldera eruptions (e.g. Pike & Clow 1981; Wood 1984). ODP Site 642 on the Voring Marginal High, located approximately 150 km SW of the Hel Graben, drilled through an upper series of tholeiitic flows before drilling 142 m of dacitic rocks, including ignimbrites (Eldholm et al. 1989). Based on the flow chemistry, Taylor & Morton (1989) concluded that these rocks were sourced from a shallow magma chamber and were derived from partial melting of the continental crust. The ignimbrites prove that acidic explosive eruptions took place in the outer Voring margin prior to extrusion of tholeiitic lava associated with break-up. The age of the dacite sequence in ODP 642, derived from two single-crystal 40Ar/39Ar dates, is 54.3±0.5 and 55.6±2.0 Ma (Late Paleocene–earliest Eocene) (Sinton et al. 1998). Eldholm et al. (1989) suggested that the lower series dacies correspond to the North Sea Sele Formation, which contains graded ashes of both silicic and basaltic composition (Knox & Morton 1988).

While a caldera explanation for the Hel Graben collapse is speculative, the unusual style of vertical collapse is more definitive. The caldera concept is only one of several potential causes of such collapse. What collapse features have in common, however, is the removal of a volume of material at depth, be it molten rock in a magma chamber, dissolution or withdrawal of halite, melting of ice, mine shaft collapse or deflation of a balloon in analogue experiments (e.g. Marti et al. 1994; Branney 1995; Ge & Jackson 1998; Roche et al. 2000; Trott et al. 2002). Removal of crustal volume beneath the Hel Graben could be tied to a number of causes. Caldera eruption is one, magma withdrawal or crustal delamination during break-up are other possibilities. The nature of the mid-Norwegian marginal high remains unresolved, and this enigmatic feature has been interpreted to be made up of transitional crust and is, thus, a candidate for laterally displaced magmatic rocks.

We have argued in an earlier paper (Lundin & Doré 2011) that the compressional tectonic events described above were possible because the area was prone to deformation, as a consequence of lithospheric thinning and the Early Cretaceous hyperextension. Hyperextension is suggested to lead to a significant reduction of lithospheric strength due to: (a) thinning of the crust by a total stretching factor of 3–4 or more; and (b) associated partial serpentinization of the upper mantle. Weakening related to hyperextension and associated partial serpentinization
of the upper mantle has been demonstrated numerically (Lundin et al. 2012; Wienecke & Lundin 2012). Late Cretaceous compressional deformation started approximately 20–40 Ma prior to break-up of the NE Atlantic, and the last compressional deformation post-dated break-up by about 40 Ma. Thus, whatever the cause of the compressional events, it is unlikely that they can be attributed to the break-up process.

In principle, the compressional deformation could be thin-skinned and constrained to the crust; that is separated from the mantle by partially serpentinized uppermost mantle. However, such a solution provides a problem in balancing an undeformed underlying mantle from a deformed overlying crust. Alternatively, the entire lithosphere has been deformed (cf. Cloetingh & Burov 2010), and, if so, that would suggest that such lithospheric weakening is long-lived (c. 115 Ma) and that the lithospheric strength does not increase as rapidly as suggested by, for example, Close et al. (2009).

**IMPLICATIONS FOR THE PETROLEUM SYSTEM**

Widely spaced fault blocks dismembered by large-heave low-angle faults are to be expected from hyperextension (cf. Osmundsen & Ebbing 2008; Péron-Pinvidic & Manatschal 2009). Therefore, a patchy distribution of the Upper Jurassic source rock is likely, since it would have been part of the pre-rift succession. More importantly, the source rock would have already been buried deeply already during the Early–mid-Cretaceous, causing maturation of the source rock and expulsion of hydrocarbons before or close in time to the deposition of Upper Cretaceous reservoirs, and certainly well before trap development related to Late Cenozoic compressional inversion (e.g. the Naglfar and Vema domes) (Doré et al. 1999). A minor late gas charge, probably from leaner source rocks post-dating the Jurassic, is found in the Nise Formation within nearby inversion-related traps (Snefrid and Hakland discoveries).

The proposed weakness related to hyperextension allowed the mid-Norwegian margin to deform readily. Latest Turonian development of the Vigrid Syncline generated a fairway for deposition of the Santonian–Campanian Nise Formation turbidites (Fig 1). Inversion by the Vema–Nyk Anticline probably blocked this fairway and diverted the subsequent Maastrichtian Springar Formation turbidites, mainly to the outer (western) flank of the fold.

The Maastrichtian–Early Paleocene Vema–Nyk Anticline may have formed early enough to receive charge from an Upper Jurassic source rock, but regardless of whether hydrocarbons were originally trapped in this large structure, the fold was breached by faulting and erosion in Late Paleocene time (Fig. 6c). Much of the hydrocarbon charge will probably have been lost to the surface. The Aasta Hansteen (Luva) Field, an approximately 1.5 tcf (trillion cubic feet) gas accumulation in the Nise Formation on the Nyk High associated with a well-defined seismic flat spot (Goodall et al. 2002), may represent remnant charge of, more probably, a late gas charge.

The previously unrecognized collapse of Hel Graben led to misidentification of the reservoir drilled on the Naglfar Dome by well 6706/6-1 (Fig. 8). However, regardless of the age of the reservoir, the main challenge of this prospect still relates to the late (probably post-charge) development of the structure.

**CONCLUSIONS**

- The mid-Norwegian margin was originally part of a hyperextended Early Cretaceous basin chain. The hyperextension caused a significant and arguably long-lived (c. 115 Ma) reduction of the lithospheric strength, making the area prone to multiple phases of compressional deformation. The long-lived weakness of the margin, here related to crustal hyperextension and partial serpentinitization of the mantle, suggests that lithospheric strengthening does not occur as rapidly as some authors propose.
- The interplay between Cretaceous and Cenozoic compressional phases, and intervening pre-break-up extension, resulted in a complex and variable pattern of vertical motions across the northern Voring Basin. Late Cretaceous compressional inversion may have been initiated initiated in Cenomanian–Turonian time but no later than intra-Maastrichtian time. The compression created or enhanced the characteristic syncline–anticline architecture of the Voring Basin. It is suggested that features such as the Vigrid and Naglrind synclines, most often assumed to represent passive post-extensional subsidence features, were a consequence of this compressional deformation. The inversion is regarded as a southerly outpost of the more significant Late Cretaceous compressional activity documented on the Barents Sea margins.
- Prior to latest Cretaceous inversion, the Vigrid Syncline continued northwards, at least through the Hel Graben but possibly also outboard of the Utrogen Ridge.
- The latest phase of Late Cretaceous inversion occurred in the Vema–Nyk–Hel area. A major updip area, the Vema–Nyk Anticline started forming in Maastrichtian time and inverted the palaeo-Vigrid Syncline.
- Subsequent pre-break-up extension was mainly of Paleocene age and was focused on the anticlines. Major collapse occurred on the western flank of the Vema–Nyk Anticline forming the Hel Graben, an enigmatic structure lacking usual rift geometries. Anticline collapse also took place along the western flank of the Gjallar Ridge and in the Fenris Graben. Less pronounced extension occurred along the Ugard High–Fles Fault Complex.
- After Early Eocene break-up, the northern Voring Basin was imprinted by further mild compression, modifying the Nyk High and Hel Graben area, and forming the Vema and Naglfar domes.

The ideas presented here date back almost a decade, and several Statoil colleagues working on production licenses 217 and 218 were consulted at the time. We are indebted to their comments. We express our gratitude to Statoil and former partners in production licenses 217 and 218, BP and Conoco-Phillips. The views presented here are our own and do not necessarily represent a company view. We are thankful for constructive comments from two anonymous reviewers.

**REFERENCES**

Repeated inversion and collapse


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