Repeated inversion and collapse on the Late Cretaceous – Cenozoic northern Vøring Basin, 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 Naglfar Domes. A prominent Maastrichtian-Paleocene pre-breakup phase of compression inverted the northern prolongation of the latest Turonian Vigrid Syncline. This syncline was the fairway for the c 1 km thick Santonian-Campanian Nise sandstone, shed from NE Greenland and/or the western Barents Sea margin. The inversion focused on the Vigrid 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 Naglfar and Vema Domes.

More speculativly, the development of the Vigrid 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 postdated the hyperextension by c 110 m.y., which, suggests that the weakening is long-lived and that lithosphere has not been strengthened significantly through time.

Key words: NE Atlantic, serpentinization, inversion, hyperextension, folding, compression, collapse

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 c 250 m.y. 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 which “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 versus 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. Doré et al, 2008, Johnson et al. 2005, 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 multi-phase 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 (Perez-Gussinye & Reston, 2006; Sutra & Manatschal, 2012), in turn permitting faults to penetrate the entire crust, and thereby hydrate the upper mantle.

Structural features of the north Vøring Basin

The Vigrid Syncline is a latest Turonian (Brekke et al, 2001) through Paleocene sub-basin in the outer Vøring 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 to 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 to 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 southwest boundaries to Hel Graben are defined by the Rym Fault Zone, which here is considered to be a flexure or faulted flexure. The northwest 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).

The Vigrid Syncline spans the Vøring 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 to Paleocene succession onlaps westward 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, bound by west-throwing normal faults (e.g. Lundin & Dore, 1997; Ren et al, 2003; Gernigon et al, 2004). These faults have been interpreted to be of Late Cretaceous to Paleocene age (op. cit.). 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 Vøring Basin was reshaped into broad folds in Cenomanian-Turonian time (Brekke 2000; Brekke et al., 2001; Lundin & Doré, 2011). Apart from the sources mentioned above, 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 syncline is not underlain by a rifted terrain, but rather by a relatively uniformly thick Cretaceous succession. Thus, the syncline is clearly not a thermal response to rifting. 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 Utrøst Ridge in the outer Lofoten margin. Seismic data reveal onlap of Late Cretaceous strata against the eastern side of the Utrøst 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 northwestern 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 (Cloetingh & Burov, 2010). Folding of the basin started c 40-60 m.y. after the Early Cretaceous hyperextension. The wavelength of the Vigrid Syncline fold is in 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, an over 1000 m thick sequence (in the former syncline axis) of clean deep water sandstones (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 Fm 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 westward thickening of the Nise Fm, from the Utgard High through the Någrind Syncline to the Nyk High. The Nise Fm 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 postdate 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 Fm (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-southeastward from NE Greenland and the northwestern 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 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 rise of the Vema-Nyk Anticline and folding of the Någrind Syncline (Fig. 10). This deformation is considered a clear compressional episode that preceded break-up.

Paleocene pre-breakup faulting

Pre-breakup extension, beginning in the latest Cretaceous but mainly of Paleocene age, and major marginal magmatism of mainly Paleocene to 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 Vøring 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, ie essentially spanning the Campanian to 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 compression causing the inversion of the Vigrid Syncline. However, lines presented by Ren et al. 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 Sycline infilled 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-breakup faulting occurs on the anticlinal crests – the Nyk High, the Utgard High, the Gjallar Ridge, and the Utrøst Ridge, suggesting that the Late Cretaceous anticlines were unstable and provided a locus for later (mainly Paleocene) extension.

Evolution 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 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 Hvitvies (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, 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). Due to the considerable difference in biostratigraphic dating, the Hvitveis well has been re-dated numerous times, more than any other Norwegian well. However, a Paleocene age at TD now appears undisputable (Williams, 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. 5 B) shows infill in the collapsed Hel Graben, and draping of the Neogene isopach (Fig. 5C) reveals the location of the present day Vema Dome, c 9 km further west of the palaeo-dome.

The evolution is also well expressed by an E-W 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 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 southeastern 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 c 4.5-5 seconds two-way-time depth. This unconformity is correlated with the Late Paleocene unconformity penetrated by exploration well 6706/11-1 (Vema Dome), where the hiatus spans the Early Paleocene and Late Maastrichtian. Notably, the “stripy” strata in Hel Graben are not rotated down against the Nyk High fault system and signs of a syn-rift wedge expanding towards the fault system are lacking (Fig. 8). Rather, the “stripy” strata in Hel Graben thin toward and onlap upwards against the unconformity bounding the Nyk High scarp, resembling geometries typical of collapse features. Strata onlapping the unconformity are clearly Paleocene and younger in age, as the 6706/6-1 well demonstrates (Williams & Magnus, 2010). The Nise Formation and older strata are not imaged in Hel Graben.

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 Vøring 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 southwestern 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). Farther north, Svalbard was emergent through the entire Late Cretaceous, with erosion apparently increasing northwards across the archipelago (Steel & Worsley, 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 Wandel Sea Basin of northeast 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 above. 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 Danmarkshavn Ridge and to the northwestern 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 og the Gjallar Ridge (e.g. Lundin & Doré, 1997; Ren et al, 2003, Gernigon et al, 2004). 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 onlaps 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 have 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, 2004), 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 if 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 & Dore, 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 Anticline and the associated development and fill of the Någrind Syncline (Fig. 3). Therefore, a conceivable scenario is: a) compressional buckling of the Vøring Basin in Late Turonian time with the development of the Vigrid Syncline, b) continued inversion of the Danmarkshavn Ridge off NE Greenland (and off the greater Svalbard area) during Santonian-Campanian, and c) rise of the Vema-Nyk Anticline 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 predominantly was 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 trap door-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 an acidic caldera (ref). ODP site 642 on the Vøring Marginal High, located c. 150 km southwest 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 and 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 outer Vøring margin prior to extrusion of tholeiitic lava associated with break-up. The age of the dacitic sequence in ODP 642, derived from two single-crystal ^{40}Ar-^{39}Ar 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 dacites correspond to the North Sea Sele Fm, 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 definite. 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 analog experiments (e.g. Marti et al., 1994; Branney, 1995; Ge & Jackson, 1998; Roche et al., 2000; Troll 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 deformation events described above were possible because the area was prone to deformation, as a consequence of lithospheric weakening by 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 et al, 2012). Late Cretaceous compressional deformation started c 20-40 m.y. prior to break-up of the NE Atlantic and the last compressional deformation postdated break-up by c 40 m.y. Thus, whatever the cause of the compressional events, they unlikely can be attributed to the break-up process.

In principle, the compressional deformation could be thin-skinned and constrained to the crust, i.e. 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 is deformed (cf Cloetingh & Burov, 2010), and if so, that would suggest that such lithospheric weakening is long-lived (c 115 m.y.) and that the lithospheric strength does not increase as rapidly as suggested by e.g. 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 (c.f. Osmundsen & Ebbing, 2008; Peron-Pindivic and 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 to 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. Naglfar and Vema Domes) (Doré et al, 1999). A minor late gas charge, probably from leaner source rocks postdating the Jurassic, is found in the Nise Formation within nearby inversion-related traps (Snefrid and Haklang 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, a c 1.5 TCF 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 likely 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 development of the structure.

Conclusions

1) 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 m.y) 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 serpentinization of the mantle, suggests that lithospheric strengthening does not occur as rapidly as some authors propose.

2) The interplay between Cretaceous and Cenozoic compressional phases, and intervening pre-breakup extension, resulted in a complex and variable pattern of vertical motions across the northern Vøring Basin

3) 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 Vøring Basin. It is suggested that features such as the Vigrid and Någrind Synclines, most often assumed to represent passive post-extensional subsidence features were a consequence of this compressional deformation.

4) Prior to latest Cretaceous inversion, the Vigrid Syncline continued northwards, at least through the Hel Graben but possibly also outboard of the Utrøst Ridge.

5) The latest phase of Late Cretaceous inversion occurred in the Vema-Nyk-Hel area. A major updomed area, the Vema-Nyk Anticline, started forming in Maastrichtian time and inverted the palaeo-Vigrid Syncline.

6) Subsequent pre-breakup 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 Utgard High/Fles Fault Complex.

7) After Early Eocene break up, the northern Vøring Basin was imprinted by further mild compression, modifying the Nyk High and hel Graben area and forming the Vema and Naglfar Domes.

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Figure captions

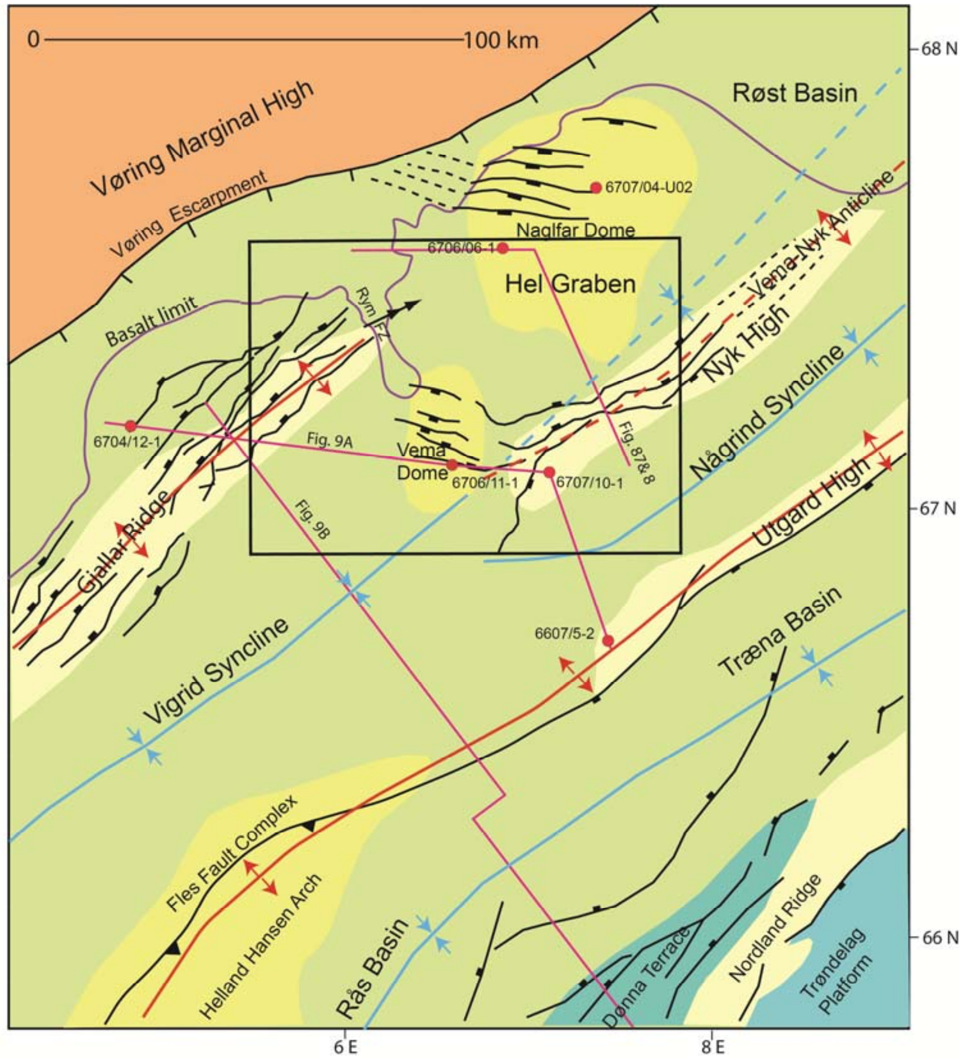

Fig. 1 Structural features map of northern mid-Norwegian margin (after Blystad et al, 1995). Inset box marks area of figures 4 and 5. Profiles are labelled with figure number.

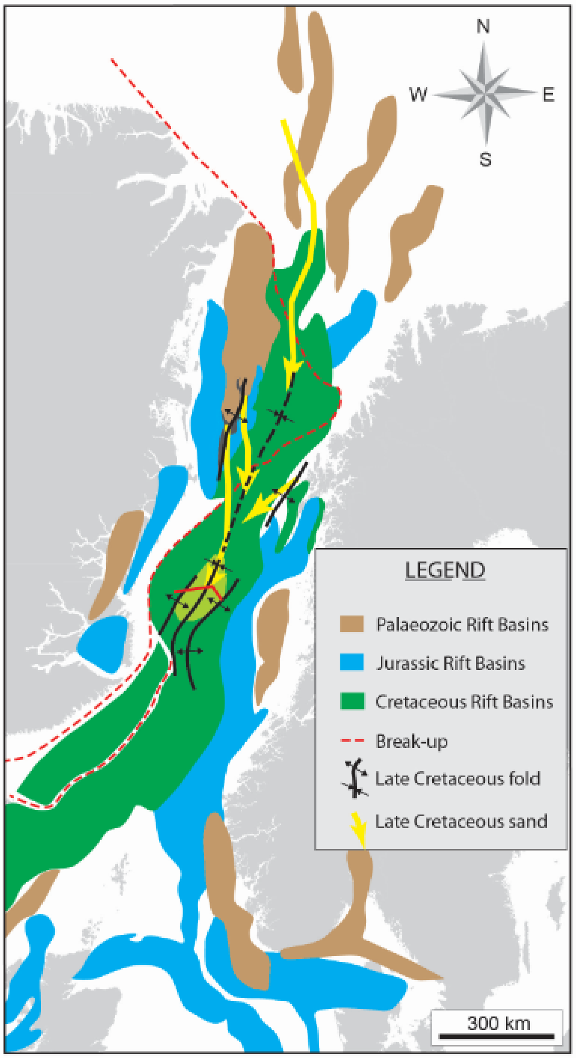

Fig. 2 Pre-breakup plate reconstruction to 53 Ma, illustrating how younger rifts overprint older at an oblique angle and how erosional products from inverted areas were shed into the palaeo Vigrid Syncline. Red profile is Fig 9b.

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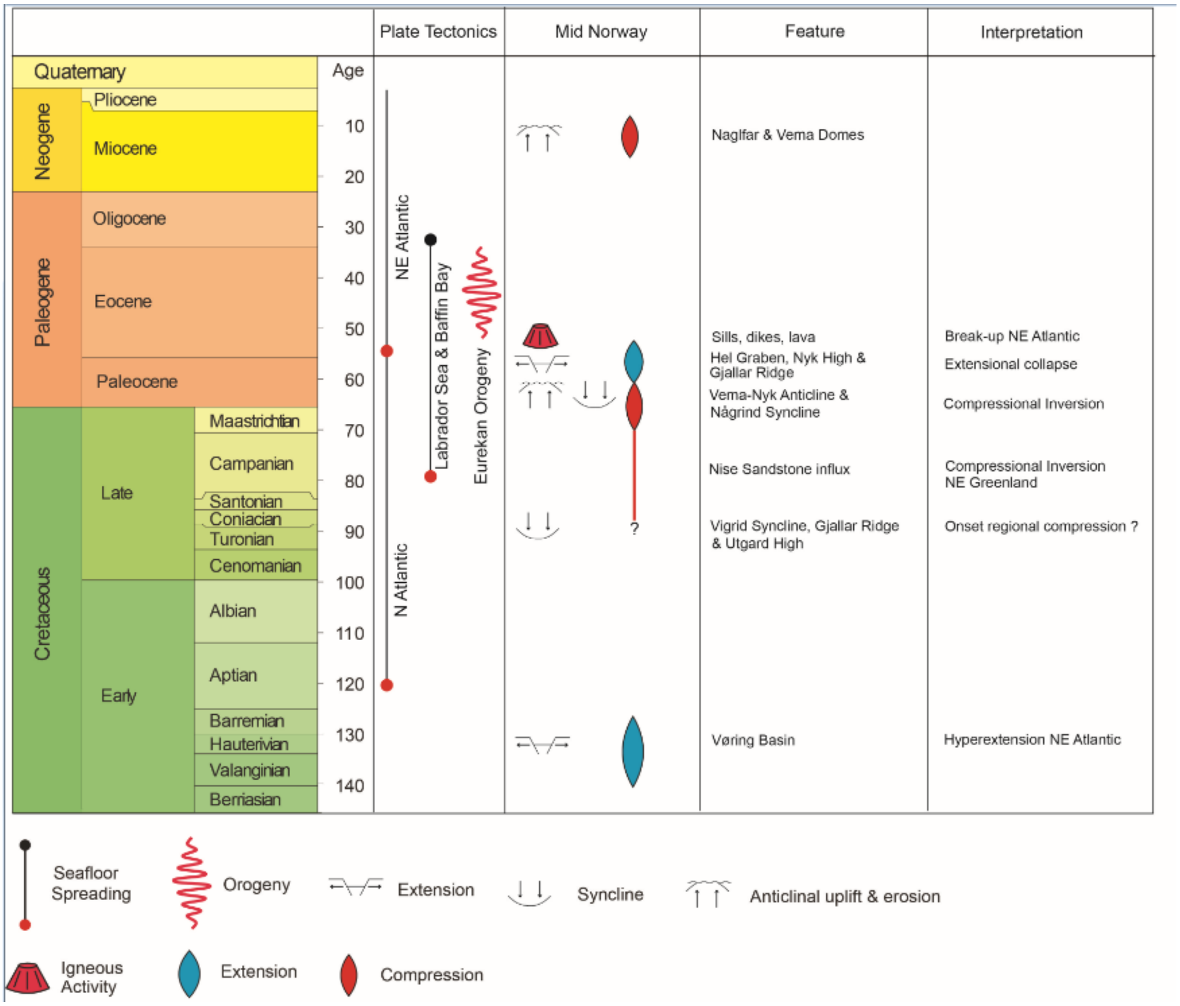

720 Fig. 3 Tectonic events chart.
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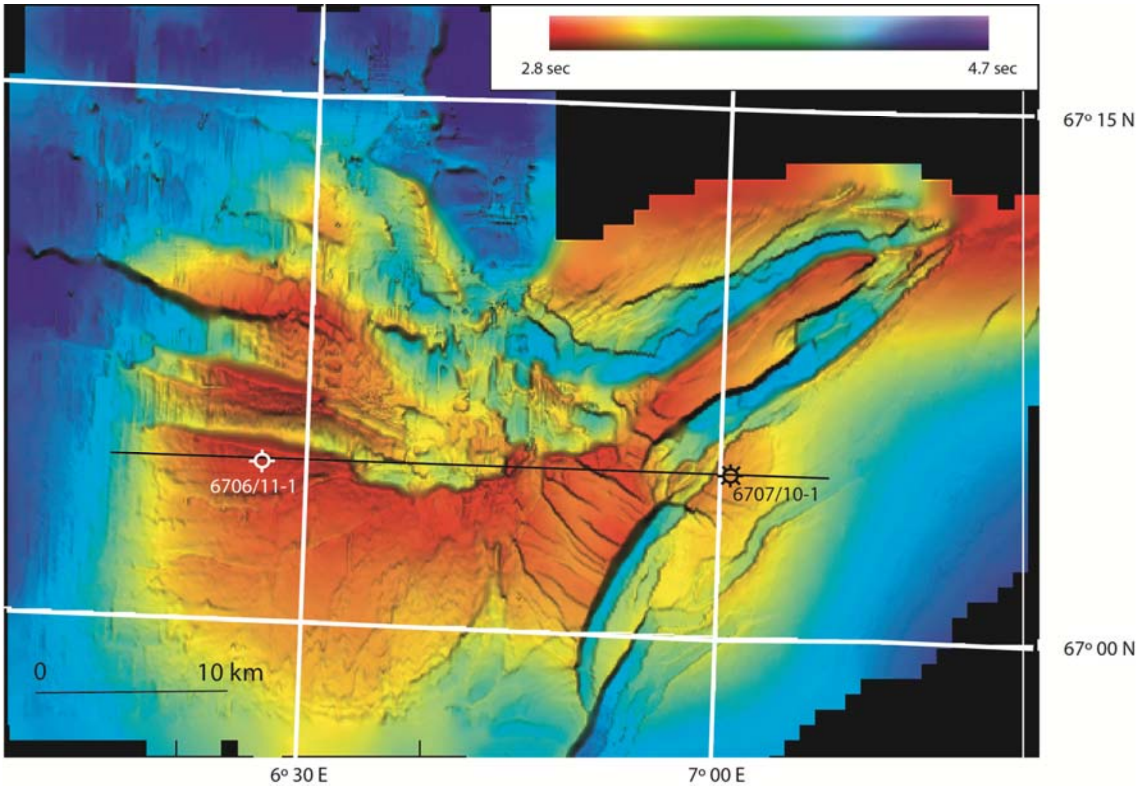

Fig. 4. Shaded relief structural map of the present day Vema Dome- Nyk High area at top Campanian level (Nise Formation) level.

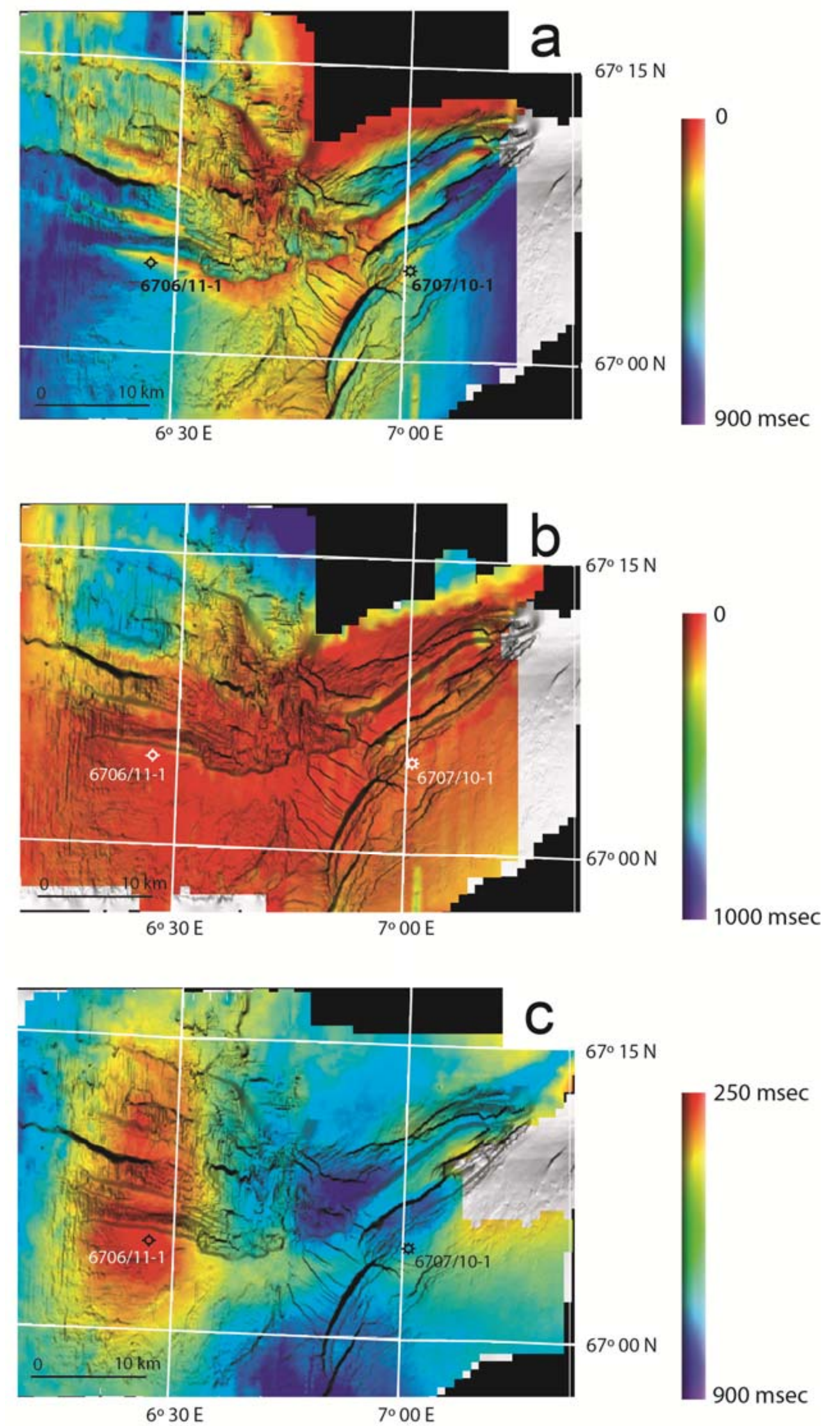

Fig 5. Shaded relief maps, with isochore maps draped over the Campanian structure map of Fig. 4. Colours indicate isochore thickness in relationship to the palaeo-Vema Dome structure. a) Maastrichtian isochore demonstrating erosional truncation above the palaeo-Vema Dome, b) Paleocene isochore illustrating collapse into Hel Graben, c) Neogene isochore illustrating inversion of the current dome.

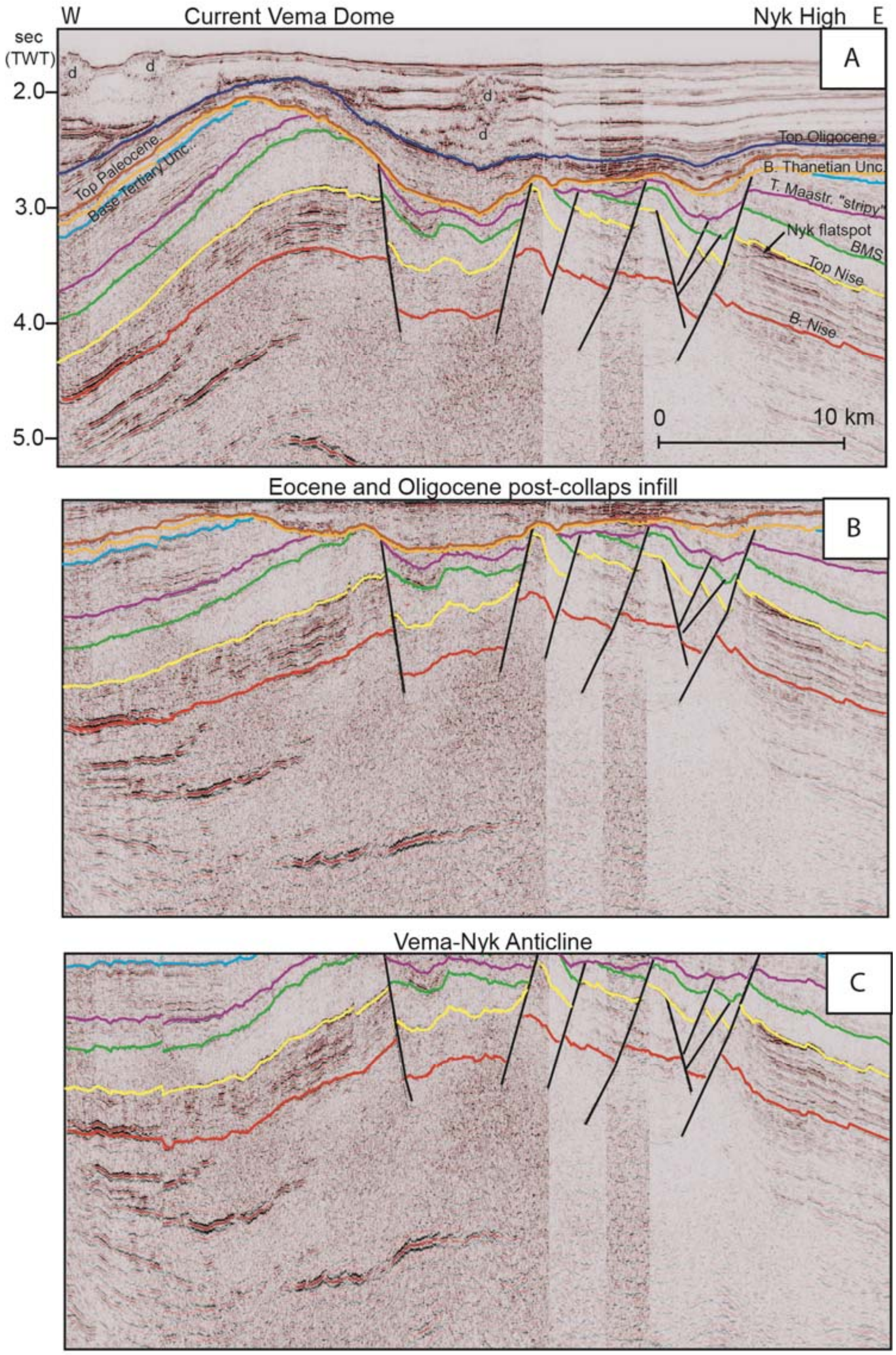

Fig. 6. E-W seismic profile across the Vema Dome and Nyk High revealing main structural stages. A: Present day, revealing the Middle Miocene Vema Dome. B: Flattened on top Oligocene, revealing Paleocene-Eocene infill after Late Paleocene collapse along the Nyk High extensional system. C: Flattened on the Base Cenozoic unconformity, revealing the Vema-Nyk Anticline.

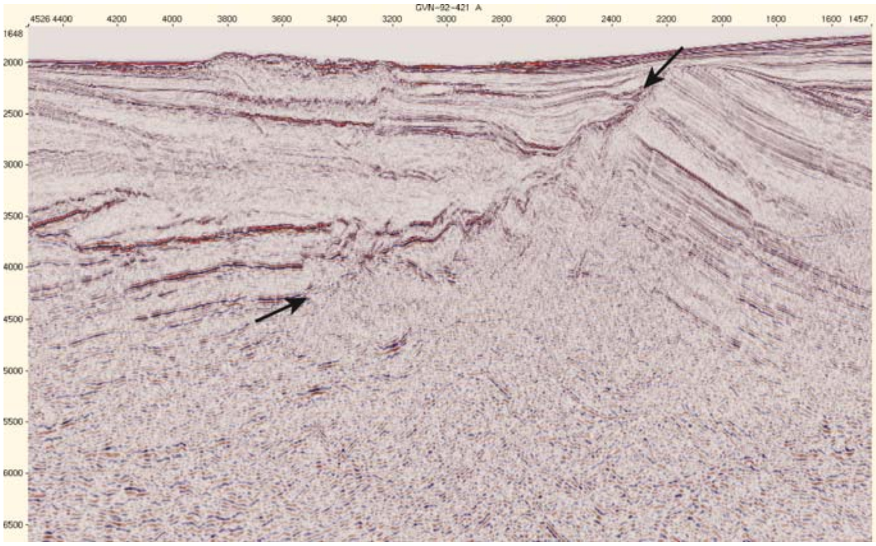

Fig. 7 NW-SE oriented seismic profile GVN92-421 across the Nyk High and eastern side of Hel Graben (for location see Fig. 1), illustrating the collapsed western flank of the Nyk High (the former Vema-Nyk Anticline). The Paleocene unconformity (marked by arrows) bounding the degraded fault scarp can be followed to at least 4.5 sec TWT. Note how the strata in Hel Graben lap on upwards against the unconformity.

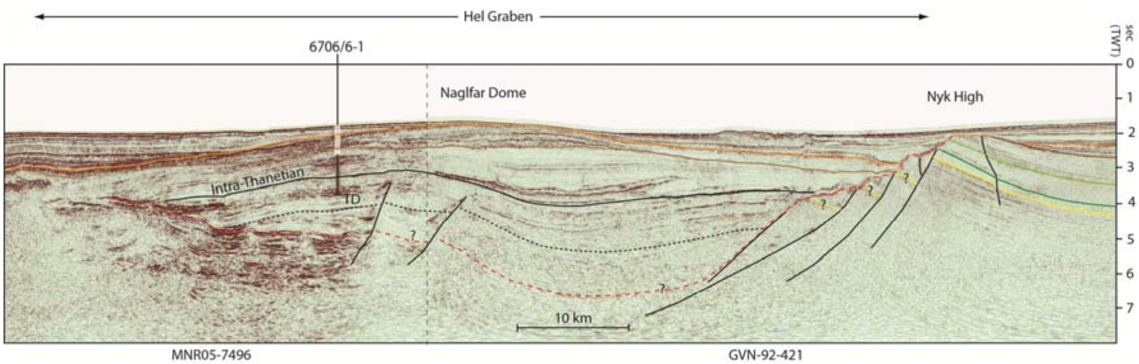

Fig. 8 NW-SE oriented seismic profile across Nyk High and southeastern Hel Graben, tying to well 6706/6-1 (for location see Fig. 1). The well terminated in Selandian age strata, which can be seen to onlap the fault scarp. The upper white part of the well had returns of cuttings to seabed while the lower gray shaded part was sampled.

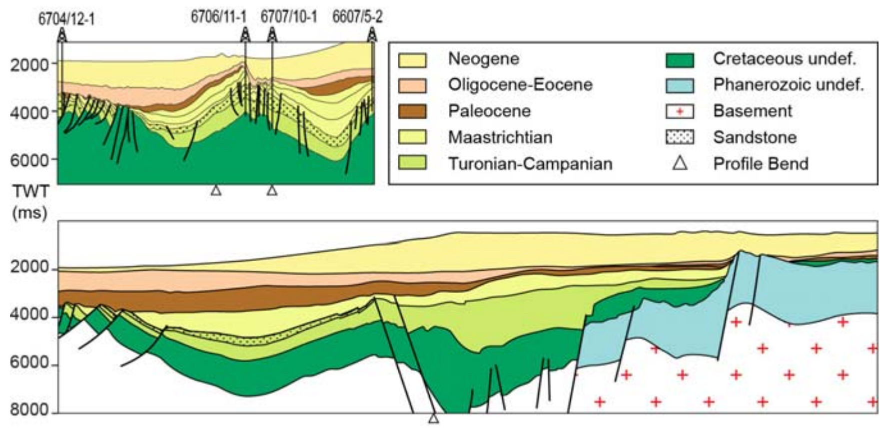

Fig. 9A) Geoseismic profile between the Gjallar Ridge (6704/12-1), Vema Dome (6706/11-1), Nyk High (6707/10-1) and Utgard High (6607/5-2) wells. The section illustrates that the Santonian-Early Campanian Nise Fm (stippled) was deposited in an unstructured saucer-shaped basin, which subsequently was inverted 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. 9B) The Turonian-Maastrichtian Vigrid Syncline (left half of profile), the Utgard High and the Rås Basin. For location see Fig 1. After Lundin & Doré (2011).

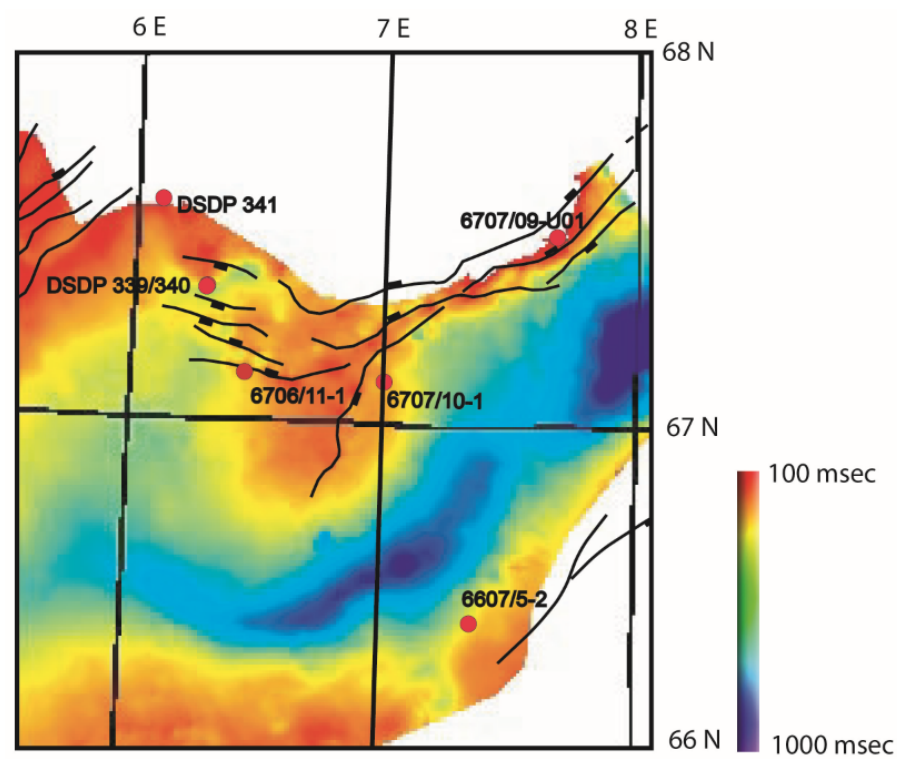

Fig. 10. Simplified Maastrichtian isochore map (TWT). The lack of Maastrichtian strata in Hel Graben is a function of difficulty of mapping below the base Thanetian unconformity. The map reveals the onset of folding of the Vema-Nyk Anticline and the Någrind Syncline.