Early Cretaceous syn-rift uplift and tectonic inversion in the Loppa High area, southwestern Barents Sea, Norwegian shelf

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Abstract

Tectonic inversion of rift basins is most commonly reported in the literature to occur after rifting has ceased. In contrast, we present evidence for syn-rift, localised tectonic inversion from the Loppa High area, southwestern Barents Sea and present a model for the formation of inversion structures as a result of differential uplift. The structures are of early Barremian to mid-Albian age (ca. 131-105Ma) and are focused in, or near pre-existing extensional boundary faults along the margins of the Loppa High. Inversion is interpreted to be the result of uplift of the high along its inclined boundary faults, leading to space accommodation problems as uplift was not properly compensated by extension in the region. The model constrains the initiation of uplift of the Loppa High to early Barremian and shows that the asymmetric margin configuration of the high may have led to a bulk clockwise rotation of the high around a vertical axis during uplift. The cause of uplift is not fully understood, but suggested to be linked to contemporaneous extreme lithospheric thinning in neighbouring basins to the west. Processes involved may include isostatic flexure, thermal heating, lithological phase changes and/or far-field stresses, although these aspects need to be further tested.

The present-day Barents Sea forms an epicontinental sea located in the northwestern corner of the Eurasian tectonic plate. It overlies a tectonically extended shelf that is comprised of a range of basins, highs and fault complexes (cf. Gabrielsen et al. 1990) and formed through multiple events of extension since the collapse of the Caledonian Orogeny (e.g. Faleide et al. 1984; 1993; 2008; Gabrielsen et al. 1990; Gudlaugsson et al. 1998; Mosar et al. 2002; Glørstad-Clark et al. 2010). Post-Caledonian (Devonian) orogenic collapse was followed by several rift-events throughout the Carboniferous to Eocene, terminating with the opening of the North-Atlantic and Arctic oceans. The southwestern Barents Sea played an important role

during final stages of rifting, which was characterized by the transition from a simple rift-system in the south to a dextral transform connecting the North-Atlantic rift to the Arctic rift system in the northwest (Faleide et al. 2008).

Despite being subject to more than 300 m.y. of extension, several authors have reported late Palaeozoic-Cenozoic events of tectonic inversion in the southwestern Barents Sea (Ziegler 1978; Rønnevik et al. 1982; Riis et al. 1986; Berglund et al. 1986; Sund et al. 1986; Brekke & Riis 1987; Wood et al. 1989; Gabrielsen & Færseth, 1989; Gabrielsen et al. 1990; 1997; 2011; Vågnes et al. 1998; Grogan et al. 1999; Henriksen et al. 2011; Glørstad-Clark et al. 2011; Faleide et al. 2015). The most prominent examples of inversion in the region are found around the Loppa High (Fig. 1), where uplift of a late Triassic - mid Jurassic depocenter in the early Cretaceous caused the high to form an island (Wood et al. 1989; Gabrielsen et al. 1990; Faleide et al. 1993a; Glørstad-Clark et al. 2011). The uplift was contemporaneous with transpression along the Bjørnøyrenna Fault Complex (Gabrielsen et al. 1997) and wrench-related tectonic inversion in the region (Rønnevik et al. 1982; Gabrielsen, 1984; Riis et al. 1986; Berglund et al. 1986; Sund et al. 1986; Brekke & Riis 1987; Gabrielsen & Færseth 1988). Tectonic inversion also occurred in the region in the late Cretaceous – Palaeocene due to head-on (fault-perpendicular) contraction along the Bjørnøyrenna Fault Complex (Gabrielsen et al. 1997) and along the margins of the Veslemøy High and the Senja Ridge (Fig. 1; Riis et al. 1986; Brekke & Riis 1987; Breivik et al. 1998). Other events of inversion include latest Palaeocene-Eocene transpression along the transform Senja Shear Zone margin in the west (Grogan et al. 1999; Faleide et al. 2008; 2015) and a Miocene SE-directed contraction (present coordinates) that is likely related to ridge push affiliated with the development of the mid-ocean Knipovich Ridge in the northwest (Gabrielsen & Færseth 1989; Pascal et al. 2005; Engen et al. 2008; Faleide et al. 2015; Gac et al. 2016).

This paper focuses solely on the early Cretaceous phase of the tectonic inversion event. Although this phase of inversion has long been recognised, the exact timing and understanding of its driving mechanism(s) is not yet fully constrained. We therefore describe the tectonic inversion structures that are associated with this event, and aim at constraining its timing and mechanism of initiation and development. The observations are set in a regional context and a tectonic model for the early Cretaceous tectonic development is presented.

Geological Setting

Areas involved in the early Cretaceous phase of inversion include (i) the Loppa High and the Polhem Subplatform (ii) the Hammerfest Basin and (iii) the Bjørnøya and Tromsø basins (Fig 1). Based on hitherto published information, these structural elements are described below.

The Loppa High is bordered by the Bjarmeland Platform in the east and is separated from the Polhem Subplatform to the west by the Jason Fault Complex (Fig. 1; Glørstad-Clark et al. 2011). The Polhem Subplatform, which was part of the greater Loppa High throughout much of its history, is bordered by the Ringvassøy-Loppa Fault Complex to its southwest and the Bjørnøyrenna Fault Complex to its northwest. The northeastern segment of the latter fault complex also defines the boundary between the Loppa High and the Bjørnøya Basin (Fig. 1).

The Loppa High developed through several events of subsidence and uplift. Its predecessor, the Selis Ridge (also known as the “palaeo-Loppa High”, see Sund et al. (1986); Fig. 1) is now expressed as an easterly-tilted high buried within the Loppa High. It formed by uplift of the footwall of the westerly dipping Ringvassøy-Loppa and Bjørnøyrenna fault complexes in late Carboniferous, early Permian, late Permian and early to middle Triassic (Riis et al. 1986; Wood et al. 1989; Gudlaugsson et al. 1998; Glørstad-Clark et al. 2010; 2011). The Polhem Subplatform formed as a down-faulted portion of the Selis Ridge in the early to mid-Triassic (Gabrielsen et al. 1990). By the middle Triassic the Selis Ridge became expressed as a pronounced north-south striking, elongated structural high acting as a barrier to sediments (Gudlaugsson et al. 1998; Glørstad-Clark et al. 2010). Subsequently the Selis Ridge subsided and a major sediment depocenter was established atop of the ridge by late Triassic times. In the late Jurassic/earliest Cretaceous, a wider platform around (and including) the Selis Ridge and Polhem Subplatform again became uplifted, causing the late Triassic - mid Jurassic depocenter to form a sub-aerially exposed Loppa High (Fig. 1; Wood et al. 1989; Gabrielsen et al. 1990; Faleide et al. 1993a; Glørstad-Clark et al. 2011). The uplift is estimated to have been on the order of 300 metres (see diagrams in Clark et al. 2014). Erosion of the high and deposition of sediments along its flanks suggest gradual erosion and subsidence of the Loppa High in the early Cretaceous, bringing the Loppa High in level with the wider Barents Sea shelf by the onset of the Late Cretaceous (Glørstad-Clark et al. 2011).

The Hammerfest Basin is situated to the south of the Loppa High and is separated from the high by the southerly dipping Asterias Fault Complex (Fig. 1). This basin is delimited by the Ringvassøy-Loppa Fault Complex in the west, marking the down-stepping array of normal

faults to the deeper Tromsø Basin further west (Gabrielsen 1984). To the east, the Hammerfest Basin gradually shallows and flexes to become the Bjarmeland Platform, while its southern boundary is defined by the north- to northwest-dipping Troms-Finnmark Fault Complex (Gabrielsen et al. 1990).

The Hammerfest Basin was subject to extension throughout the Carboniferous-Eocene and its interior is characterised by a system of late Jurassic – early Cretaceous E-W-striking faults that comprises a range of minor horsts, grabens and half-grabens. On a larger scale, these define an E-W-striking arch that is oriented parallel to the basin axis. All these structures are most conveniently defined at the base of the Cretaceous sequence. The general basin configuration and the central arching of the basin axis have been ascribed to interaction between first, second and third-order normal faults (Gabrielsen, 1984). Furthermore, it has been suggested that the deformational style indicates that the margins of the Hammerfest Basin were partly influenced by strike-slip reactivation in the late Jurassic to early Cretaceous (Riis et al. 1986; Berglund et al. 1986; Sund et al. 1986; Gabrielsen & Færseth, 1988) as a part of regional wrench tectonics (Ziegler 1978; Rønnevik et al., 1982; Riis et al. 1986) likely caused by the oblique reactivation of pre-existing faults due to changes in regional stress. This was assumed to result in inversion occurring along the western segment of the Asterias Fault Complex as fault-perpendicular contraction by Riis et al. (1986) and Gabrielsen & Færseth (1988). Alternatively the inversion may have been affiliated with strike-slip forming a Hauterivian-Aptian positive half-flower-like structure as suggested by Gabrielsen et al. (2011). Transtension in the Swaen Graben as suggested by the presence of master faults steepening with depth thus forming assumed positive and negative flower structures (Gabrielsen et al. 1993) occurred contemporaneously with inversion in the Hammerfest Basin and is therefore possibly genetically linked.

The Bjørnøya and Tromsø basins (Fig. 1) formed through rifting in the Carboniferous and Permian-early Triassic as is characterised by Permo-Carboniferous evaporite diapirs in both basins. Late Jurassic-earliest Cretaceous extension was followed by accelerating subsidence and accumulation of very thick sediment sequences of early Cretaceous age as demonstrated by the down-faulting of Jurassic sediments to c. 13 km depth in the Bjørnøya Basin across the Ringvassøy-Loppa and Bjørnøyrenna fault complexes (Rønnevik et al. 1982; Gabrielsen et al. 1990; Faleide et al. 1993b; 2008; Clark et al. 2014).

In summary, previous literature suggests an early Cretaceous period of composite tectonism in the southwestern Barents Sea, with distinct enhanced subsidence in the Tromsø and Bjørnøya basins, uplift of the Loppa High, and tectonic inversion that is likely related to regional wrenching.

Database

This study utilises 2D reflection seismic data that are partly public data from the DISKOS database, and partly non-public data made available by TGS and ENI Norge.

Seismostratigraphic markers were picked using available public well data and are time-correlated in the Hammerfest Basin using biostratigraphic data from wells 7120/9-1 and 7121/7-1 and lithostratigraphy and chronostratigraphy from NORLEX (Figs. 1 and 2; Worsley et al. 1988, Gradstein et al. 2010). On the Polhem Subplatform and in the Bjørnøya and Tromsø basins, the seismic markers were time-correlated using biostratigraphic data from wells 7220/5-1, 6-1 and 7-1 (Figs. 1 and 2 and chronostratigraphy according to NORLEX. Depth conversion of regional grids has been done using the HiQbe™ velocity model (courtesy of First Geo AS and TGS-NOPEC Geophysical Company ASA) in order to obtain the geometry of the described structures.

Inversion structures

Several fault complexes and other structural elements in the southwestern Barents Sea display geometrical characteristics that are indicative of tectonic inversion. Some of these structures have previously been described in the literature, while others have not. Terminology and concepts used in this paper are given below and followed by the description of early Cretaceous tectonic inversion structures in the southwestern Barents Sea and discussion of their genesis.

Terminology and concepts

Tectonic inversion is defined as the reverse reactivation of normal faults due to a change in the regional stress, resulting in uplift that predominantly affects the hanging wall relative to a selected regional reference stratigraphic level (Cooper et al. 1989). Tectonic inversion is commonly separated into localised (focused) and regional (distributed) inversion based on the significance of inversion within a rift (MacGregor 1995; cf. Cooper & Williams, 1989; Buchanan & Buchanan, 1995). Whilst *regional inversion* commonly refers to the inversion of

entire basins, *localised inversion* is often manifested as inversion structures with a local significance forming along reactivated normal faults.

A diagnostic criterion for recognizing and quantifying localised tectonic inversion is the identification of the “null point” on inverted extensional faults (Fig. 3a; cf. Cooper & Williams, 1989; Buchanan & Buchanan, 1995; Turner & Williams, 2004). The null point refers to a point along an inverted extensional fault that separates strata with normal fault displacement below and reverse fault displacement above. Due to the long rift history in the southwestern Barents Sea, however, the extension to shortening ratios seems too high for any null points to be detectable, rendering the use of the null-point criterion less relevant in the region. Alternative criteria for identifying reverse reactivation of normal faults are therefore needed and include recognition of the following features: a) inverted depocentre/growth wedges (without formation of null points), b) contracted fault blocks and deformed fault planes, c) forced folds with or without the development of hanging wall reverse faults and d) structures related to secondary contractional deformation of rift basins including the formation of folds and “snake-head structures” (Allmendinger 1998) formed by reverse reactivation of faults (Fig. 3a-d). The timing of tectonic inversion is constrained by identifying pre-, syn- and post-rift sediments and their association with syn- and post-inversion sedimentary sequences (Fig. 3a; see also Turner & Williams, 2004).

The Loppa High

The interior of the Loppa High constitutes an asymmetric high of sub-Carboniferous rocks that shallows westwards to include the Selis Ridge (Figs. 1 and 4; see also Wood et al. 1989; Glørstad-Clark et al. 2011). The Selis Ridge formed during the Carboniferous and Permian events of uplift and defines a N-S trending palaeo-high so that its eastern flank is onlapped by Carboniferous and Permian sedimentary units. The ridge is unconformably overlain by upper Triassic-mid Jurassic sedimentary sequences that were uplifted during the early Cretaceous to form the Loppa High. These sequences show a distinct thickening from the Bjarmeland Platform and westward onto the present day Loppa High (Fig. 4), where the zone of thickening of these units is characterized by a concentric shape in the map view and also marks the eastern boundary of the inverted late Triassic – mid Jurassic depocenter (Fig. 1). The concentric shape of the zone of thickening indicate that the lateral extent of the depocenter that controlled the extent of what later became uplifted, although the eastern boundary locally seems to be related to a fault present in the deeper strata (Fig 4).

The Jurassic and younger sedimentary sequences are in general missing on top of the Loppa High due to erosion. Still, lower Cretaceous sediments are locally present in a system of interacting NNE-SSW and NE-SW-oriented approximately 5 km wide grabens defined by the down-faulted upper Jurassic sequence (Figs. 1 and 4). The system of grabens links up with the Swaen Graben in the east. The graben-bounding faults converge at depth and die out in Permian evaporites (Fig. 4).

Genesis

The present-day Loppa High represents a regionally uplifted Triassic-Jurassic depocenter, as demonstrated by the distinct thickening of upper Triassic-mid Jurassic sediment sequence from the Bjarmeland Platform and westward onto the high (Fig. 4; see also Wood et al. 1989; Glørstad-Clark et al. 2011). Detailed mapping shows that the Swaen Graben link up with the narrow grabens within the interior of the Loppa High (Fig. 1) and they thus seem to be genetically linked. The role of these basins during early Cretaceous tectonic inversion will be further discussed when presenting a tectonic model later in the text.

The Polhem Subplatform

The Polhem Subplatform is comprised of several N-S-striking rotated fault blocks, which are delineated by an array of down-to-the west normal faults that are most easily identified at the base Cretaceous stratigraphic level (Fig. 5). Sedimentary wedges in the hanging walls indicate that the syn-sedimentary stage of faulting initiated in the late Jurassic and that subsidence accelerated from the early Barremian onwards. The sedimentary units which are located in the immediate vicinity of the Jason Fault Complex are characterized by the development of a series of densely spaced fault blocks comprising at least four anticlines arranged in a left-stepping, *en echelon* pattern with their fold axes at an angle of ~15 degrees clockwise to the Jason Fault Complex master fault (Fig. 1a). Seen in the cross-sections, the folds bear the characteristics of positive flower structures (Fig. 5a-c). Together they make up a N-S-striking structural high that can be traced for c. 40 km within the hangingwall of the northern segment of the Jason Fault Complex (Fig. 1a). The crests of the anticlines are locally truncated by a pronounced erosional surface (Fig. 5b). Fault blocks located further west on the Polhem Subplatform are also commonly internally folded, however, so that strata dominantly dip steeply to the east (Fig. 5a, b). Local growth wedges of Ryazanian – late Barremian age within rotated fault blocks locally display evidence for localised inversion by reverse

reactivation of graben-bounding faults and/or internal folding (Fig. 5c). The outer crests of the contracted fault blocks are locally eroded and the erosional unconformity likely correlate in time with the erosional surface that truncates the inner, *en echelon* anticlines and demonstrates that contractional deformation predated or was contemporaneous with the erosion event. The upper Barremian sequence within the growth wedges onlaps the folded lower Barremian sequence (Fig. 5b). The upper Barremian unit is characterised by later minor modification by continued folding and is onlapped by the upper Barremian - middle Albian sedimentary sequence. Based on the onlap geometry within the inverted growth wedges, the timing of inversion on the Polhem Subplatform is constrained to the time interval between early Barremian and middle Albian.

Genesis

The left-stepping, *en echelon* anticlines of the Polhem Subplatform with their fold axes oriented at c. 15 degrees clockwise to the Jason Fault Complex indicate that the folds formed mainly due to E-W oriented head-on contraction modified by sinistral shear in early Barremian to middle Albian times. This is in accordance with the internal characteristics of the inner anticlines that locally resemble positive flower structures (Fig. 5). The deformed fault blocks, faults and inverted growth wedges (Figs. 1 and 5) most likely formed by the same event of contraction, causing internal buckle-folding and inversion of normal faults as illustrated in Figure 3b.

Gabrielsen et al. (1997) also suggested an early Cretaceous phase of transpression along the Bjørnøyrenna Fault Complex. They, however, suggested a dextral sense of shear for this event, but stated that determination of fold geometry and fold orientation were constrained by wide spacing of available seismic lines.

Notably, evidence for early Cretaceous inversion is not observed along the northern segment of the Bjørnøyrenna Fault Complex. The northern part of the Bjørnøyrenna Fault Complex was, however, affected by late Cretaceous – Palaeocene head-on contraction (Gabrielsen et al. 1997). Present data also document the presence of salt diapirism in this area (Fig 1). Analysis of the late Cretaceous – Palaeocene inversion and salt diapirism are, however, beyond the scope of this paper and will not be addressed below.

The Hammerfest Basin

Several structures within and along some the marginal segments of the Hammerfest Basin display possible inversion structures.

Anticline parallel to the Asterias Fault Complex

The Asterias Fault Complex partly detaches at the level of Permian evaporites (Fig. 6). The detachment is affected by north-dipping internal reflections off-setting the top of the Jurassic sequence, here interpreted as reverse faults (Fig. 6). A distinct E-W-striking anticline is located within its hangingwall (Fig. 1b). The anticline is best defined at the base of the Cretaceous level (Fig. 6) and its axis can be followed for c. 27 km, striking parallel to master faults of the fault complex. Its full wavelength, as measured between syncline minima bounding its flanks is c. 8.3 km and its amplitude as measured from a non-horizontal baseline connecting the syncline minima bounding its flanks is c. 0.9 km.

The lower Barremian seismic marker represents the uppermost stratigraphic level that is influenced by the anticline. It is overlapped by an upper Barremian sequence. This sequence was modified by continued reverse fault activity (Fig. 6) and is overlapped by upper Barremian – lower Aptian sediments, which show no evidence for later structuring related to the anticline. The onlap relationships thus indicate that the anticline developed its major relief from early Barremian to early Aptian.

Genesis

Based on the presence of reverse faults in its interior, the anticline within the hangingwall of the Asterias Fault Complex was most likely formed by N-S directed contraction, overprinting earlier normal faults as a part of localised inversion. Horizontal shortening and the development of reverse faults led to the formation of the anticline as illustrated in Figure 3c. This is in accordance with interpretations of Riis et al. (1986) and Gabrielsen & Færseth (1988). Although it is difficult to exclude the possibility that inversion was the result of strike-slip movements along the Asterias Fault Complex as suggested by Gabrielsen et al. (2011), we conclude that the structure may satisfactorily be explained by head-on contraction alone.

Anticline associated with the Goliat hydrocarbon field

This anticline encompasses the Goliat hydrocarbon field that is located close to the intersection between E-W and NE-SW striking major segments of the Troms-Finnmark Fault Complex in the southeastern part of the Hammerfest Basin (Fig. 1; Mulrooney et al. in prep). The anticline

is most obvious at the base Cretaceous and deeper levels (Figs. 1 and 7). Its axis can be traced for c. 30 km along-strike, within the hanging wall of the NE-SW-striking segment of the Troms-Finnmark Fault Complex (Fig. 1). Its full wavelength, as measured between syncline minima bounding its flanks is c. 16 km and its amplitude (as measured from a baseline connecting the syncline minima bounding its flanks) is c. 0.9 km. It is overlapped by lower Barremian to lower Aptian strata in the northwest, indicating that the anticline acted as an intrabasinal marginal high during that time. The crest of the anticline is characterised by minor faults that truncate the base Cretaceous reflection and show evidence for reverse reactivation as they terminate upwards within the cores of minor anticlines in above-lying Ryazanian – lower Barremian sediments (Fig. 7). The axes of the minor anticlines can be traced NE-SW, paralleling the strike of underlying faults for several kilometres. The minor anticlines accordingly strike parallel to the axis of the major anticline. Their wavelengths, as measured between the syncline minima bounding their flanks are on average c. 0.5 km with an amplitude of c. 50m (as measured from a baseline connecting the syncline minima). They are overlapped by lower Aptian sediments. Accordingly, the age of both the major anticline and the minor folds at its crest is constrained to the early Barremian to early Aptian.

Genesis

The major anticline (Fig. 7) is likely the result of extension through the interaction of fault segments forming a fault-bound basement terrace with depth (Mulrooney et al. in prep). It may thus be explained as an extensional feature. The minor folds affecting the lower Barremian reflection (Fig. 7), however, are interpreted to have formed due to secondary contractional deformation and development of mild snake-head geometries caused by partial reverse reactivation of below-lying faults as illustrated in Figure 3d. Locally, minor footwall cut-offs have developed owing to horizontal contraction (Fig. 7, inset). The amount of reverse reactivation is minor and consistent with NW-SE oriented contraction causing localised inversion.

Farther west along the Troms-Finnmark Fault Complex, the Alke structure (Fig. 1; see also Fig. 9 in Stewart et al. (1995) for profile) provides an additional example of possible tectonic inversion of similar age in the Hammerfest Basin. The Alke structure is affected by a local ramp-flat-ramp geometry of the Troms-Finnmark Fault Complex, but we suggest that the pronounced geometry of the structure indicate later contractional modification.

Central arch of the Hammerfest Basin

A central arch strikes E-W within the interior of the Hammerfest Basin, parallel to the basin axis (Fig. 1 and 6; Gabrielsen 1984; Berglund et al. 1986). It is most clearly observed at the base of the Cretaceous sequence and the arch axis can be followed for c. 80 km. The arch has a wavelength of c. 65 km, as measured between syncline minima bounding its flanks, and has an amplitude of c. 2.2 km (measured from a non-horizontal baseline connecting the syncline minima bounding its flanks). The arch is abruptly truncated by the Ringvassøy-Loppa Fault Complex in the west and gradually flattens towards the east. Internally, the arch is truncated by a north-dipping fault array with a combined displacement of c. 1km (Fig. 6). The fault array divide the Hammerfest Basin into a southern and northern segment that together constitute two, partly rotated, large scale fault blocks of opposite vergence (Fig. 6). The hinge line of the central arch coincides with the upward-rotated northern rim of the southern fault block, thus defining the main body of the central arch. The arch is onlapped by Ryazian - upper Barremian seismic sequences from both north and south, demonstrating that the central arch (and thus the basin axis) acted as a structural high during the Ryazian – late Barremian.

Genesis

The central arch was an intrabasinal, southerly tilted high during the Ryazian-Hauterivian to late Barremian as illustrated by its onlap configurations. The genesis of the central arch has previously been discussed in the literature, ascribing it either to the interaction between first, second and third-order normal listric faults (Gabrielsen, 1984), or to N-S oriented shortening due to strike-slip movements along the E-W striking internal faults of the Hammerfest Basin (Berglund et al. 1986; Sund et al. 1986). The new generation seismic data reveals that the apex of the central arch coincides with the outer rim of the large-scale southern rotated fault block of the Hammerfest Basin and may hence explain the central arch as a product of extension. Further, the formation of the arch in the Ryazian - Hauterivian indicate that the arch formed as a response to extension in the Hammerfest Basin rather than early Barremian inversion. The above favours the interpretation of Gabrielsen (1984), suggesting that the arch is the result of the interaction between first, second and third-order normal faults. Thus, the central arch is not considered to be caused by tectonic inversion in the present work although it still remains open whether the arch was later modified by horizontal shortening related to the early Barremian – early Aptian inversion along the Asterias Fault Complex, in the Goliat hydrocarbon field area and potentially also the Alke structure.

In summary, the Polhem Subplatform itself, the structures along its western margin (the Jason Fault Complex), the Asterias Fault Complex and minor folds associated with the Goliat hydrocarbon field area show characteristics consistent with early Cretaceous localised tectonic inversion that focused along parts of pre-existing major normal faults. Inversion structures associated with the Polhem Subplatform show evidence of being modified by sinistral strike-slip (Figs 1a, 3b and 5), while inversion in the Hammerfest Basin is consistent with N-S and NE-SW-oriented head-on contraction (Figs 1b-c; 3c-d, 6 and 7). The inversion structures are associated with marginal intrabasinal highs that were subject to erosion, no sedimentation or low sedimentation rates during formation and are constrained to the early Barremian – early Aptian or early Barremian – middle Albian. It is important to stress that the inversion structures are clearly subordinate in relation to the rift activity occurring contemporaneously.

Tectonic model

According to our dating, the tectonic inversion of the Polhem Subplatform and in the Hammerfest Basin occurred contemporaneously (Fig. 8) and therefore it is logical to ascribe these events to one single tectonic event initiating in the early Barremian. The inversion is, however, restricted only to parts of major fault complexes and shows inversion structures of diverse orientation (ENE-WSW, NE-SW and N-S, Fig. 1). Previous works have suggested mechanisms involving regional wrenching events (Ziegler 1978; Rønnevik et al. 1982; Riis et al., 1986; Gabrielsen & Færseth, 1988) causing oblique reactivation and strike-slip movements along already existing faults in an effort to explain the varying nature of shortening. Accordingly, Gabrielsen & Færseth (1988) suggested that a slight clockwise rotation of the Hammerfest Basin could explain inversion along the Asterias Fault Complex and east in the Hammerfest Basin. The driving force(s) behind such wrenching/rotation, however, has not yet been analysed in full, but may be attributed to a regional stress field or alternatively to stress of local significance caused by local tectonic adjustments. The present work shows that the timing of inversion is closely linked to the uplift of the Loppa High and that areas subject to inversion are located close to the high. We therefore suggest that there is a close link between the early Cretaceous uplift of the Loppa High, wrenching and the formation of the above described inversion structures. We propose that inversion was a direct response to the uplift of the Loppa High and present the following model for the early Cretaceous tectonic inversion in the southwestern Barents Sea (Fig. 9):

The uplift of the Loppa High relative to its surroundings was likely accommodated for by normal slip along its delimiting fault complexes i.e. the Bjørnøyrenna, the Ringvassøy-Loppa and the Asterias fault complexes that all dip basinward. The geometrical relationship dictates that such uplift would lead to space accommodation problems along the flanks of the high due to its widening with depth, assuming that the high and flanking basins are laterally confined (Fig. 9a). Upward-directed movement of the high is thus likely to have been converted into horizontal compressive stress along the flanks of the high. Stress generated by this mechanism would form perpendicular to the flank being utilised for uplift (Fig. 9a). This model is fundamentally different from the development of a “classic” horst, where the widening of the horst with depth is compensated for by extension. Because separate flanks with contrasting orientations were utilised during uplift of the Loppa High, several local stress configurations may have developed, each dominated by σ_1 orientated perpendicular to the uplifted flank. The amount of shortening induced as a result of uplift may depend on (but is not restricted to) (1) the amount of vertical uplift and the dip of the fault being utilised to accommodate uplift, (2) the ability of sediments involved to compact and (3) the amount of extension occurring contemporaneously along the same fault (compensating for the widening of the high with depth).

By assuming a constant volume and fixed flanking basins (negligible compaction and extension) along a 2D section running perpendicular to, and across a fault utilised to accommodate uplift, the ratio between uplift and horizontal shortening may be given by the shortening ratio, $s_r = 1/\tan(\alpha)$, where α is the dip of fault of which uplift is accommodated (Fig 9 a-b). As no compaction of sediments and a 100% effective lateral confinement are highly unlikely assumptions, the shortening ratio must be considered a maximum estimate of shortening being generated by the discussed mechanism.

The geometrical relationship between the Asterias Fault Complex and the associated anticline caused by inversion (Fig. 6) can be used to test the applicability of the shortening ratio. The master fault segment of the western part of the Asterias Fault Complex dips 62° at the stratigraphic depth of which the anticline is located. The amount of horizontal shortening observed by the formation of the anticline (as measured between the syncline minima bounding the anticline) is calculated to $\sim 1.2\%$, corresponding to c. 180 metres. Using the shortening ratio (Fig. 9b), the amount of vertical uplift corresponding to the observed horizontal shortening is calculated to c. 340 metres. This value fits well with first-order

estimates of the early Cretaceous uplift of the Loppa High done by Clark et al. (2014, see diagrams within), giving values in the order of 300 metres.

Further, at least three mechanisms generating laterally varying stress configurations may exist: First, the Loppa High shows an asymmetric uplift along its E-W-axis, increasing westwards (Fig. 4). Hence, the western flanks of the high may thus have been subject to greater amounts of fault throw and hence larger space accommodation problems than flanks along the eastern part of the high. As an example, inversion along only the western part of the E-W-striking Asterias Fault Complex supports this (Figs. 1 and 6).

Second, variations in sediment compaction and/or amount of lateral confinement of flanking basins are likely and would significantly impact the amount of observable shortening being generated by uplift. This may be the reason why no inversion structures of early Cretaceous age are observed along the northern part of the Bjørnøyrenna Fault Complex as extension and subsidence in this part of the Bjørnøya Basin may have been greater than shortening generated by uplift at the time.

Third, the asymmetric shape of the Loppa High would lead to an unbalanced local horizontal stress fields being generated assuming all flanks are utilised for uplift. In addition, shortening occurring within the Tromsø and Bjørnøya basins were likely less confined than in the Hammerfest Basin due to ongoing extension.

The model thus implies that stress generated by uplift vary in strength and orientation leading to an unbalanced regional stress pattern. Rotation as a response to unbalanced local horizontal stress-fields being generated by uplift may thus be a source for a component of wrenching as has been suggested in the region by several authors (Ziegler 1978; Rønnevik et al. 1982; Riis et al. 1986; Berglund et al. 1986; Sund et al. 1986; Gabrielsen & Færseth, 1988; Gabrielsen & Færseth, 1989; Gabrielsen et al; 1997). In the case of the Loppa High, the resulting stress configuration could potentially have led to clockwise bulk rotation of the high around a *vertical* axis (Fig. 9c). Such rotation would explain both sinistral movements on the Polhem Subplatform generating the observed en echelon folds and also transtension in the Swaen Graben and the associated narrow grabens in interior of the Loppa High (Fig. 9c). However, it is not unlikely that far-field horizontal stresses contributed to strike-slip movements along the margins of the Loppa High in the early Cretaceous.

The inversion close to the Goliat hydrocarbon field (and potentially the Alke structure and partially the central arch of the Hammerfest Basin) is likely affiliated with horizontal stresses propagating from the Loppa High margins through basement units of the Hammerfest Basin. Numerical modelling has shown that stress is unlikely to propagate through relatively soft sedimentary cover units, but may propagate through crystalline basement for hundreds of kilometres and be expressed as passive folding of the above-lying sedimentary cover along basement-seated fault zones and or areas of high basement relief (e.g. Pascal & Gabrielsen, 2001; Pascal et al. 2005, 2006, 2010; Buiter & Torsvik, 2007; Cloething & Burov, 2011; Dore et al. 2008). Still, it cannot be excluded that the inversion structures located along the Troms-Finnmark Fault Complex are the result of far-field horizontal stresses.

The model constrains the initiation of uplift of the Loppa High to the early Barremian. It is noted that the uplift coincided with a major switch in rift activity in the region, where moderate, distributed extension in the late Jurassic/earliest Cretaceous in the southwestern Barents Sea was followed by major extension along the Bjørnøyrenna and Ringvassøy-Loppa fault complexes by the early Barremian (Fig. 8; e.g. Gabrielsen et al. 1990, Faleide et al. 1993a,b; 2008). A focus of rift activity is recognised in the entire North Atlantic region and in the Barents Sea in this period (Faleide et al. 1993b), which in the southwestern Barents Sea led to extreme lithospheric thinning in the Tromsø and Bjørnøya basins. The axis defined by the Ringvassøy-Loppa and Bjørnøyrenna fault complexes marks the position of a major basement-seated, Caledonian zone of weakness (Rønnevik et al. 1982; Gabrielsen et al. 1990; Faleide et al. 1993a,b; 2008; Ritzmann & Faleide 2007) and may explain why extension became focused in this zone.

The cause for uplift the Loppa High has been previously discussed in the literature. Wood et al. (1989) suggested that uplift was associated with fault block rotation and footwall uplift along Ringvassøy-Loppa and Bjørnøyrenna fault complexes. Such a mechanism is, however, commonly associated with uplift wavelengths from 0.1 – 15 km (Roberts & Yielding, 1991; Gabrielsen et al. 2005) and thus fails to explain the uplift of the wider Loppa High area (wavelength > 90km). Uplift as a part of rift flank uplift due to isostatic flexure has also been proposed (Glørstad-Clark et al. 2011; Clark et al. 2014). Although we agree that isostatic flexure most likely was involved in the uplift of the Loppa High, such uplift would affect the entire eastern flank of the Tromsø and Bjørnøya basins and thus cannot fully explain the uplift

of the Loppa High relative to e.g. the neighbouring Hammerfest Basin situated along the same rift flank.

We therefore conclude that one or more additional process(es) must have contributed to the uplift of the Loppa High. Such mechanisms could include far-field stresses but also uplift mechanisms related to the deeper structuring of the high and thermomechanical processes, including p-T-related mineral transitions. It is particularly noted that the high is underlain by a distinct block of thicker crust (Ebbing & Olesen 2010), which is characterised by anomalously high densities and magnetic susceptibilities at its base interpreted to represent the presence of mafic rocks (Ritzmann & Faleide 2007; Clark et al. 2014). An increase in heat flux due to lithospheric thinning in the west may have triggered uplift through thermal heating and/or phase changes in the lower mafic crust. These are, however, aspects that need to be tested and will not be further discussed herein.

Conclusions

Evidence for early Cretaceous tectonic inversion is documented on the Polhem Subplatform and in the Hammerfest Basin, southwestern Barents Sea. The inversion structures inhabit a range of orientations that are consistent with head-on (fault-perpendicular) contraction modified by sinistral transpression on the Polhem Subplatform and head-on contraction along the Asterias Fault Complex and in the Goliat hydrocarbon field area close to the Troms-Finnmark Fault Complex. The timing of formation of these structures is constrained to the early Barremian – early Aptian and early Barremian – middle Albian.

A tectonic model is presented that links the formation of the inversion structures to the uplift of the Loppa High due to space accommodation problems along the flanks of the high during uplift. The model constrains the initiation of uplift of the Loppa High to the early Barremian and explains how differential uplift and/or changing along-fault boundary conditions may have led to unbalanced horizontal stresses leading to a clockwise bulk rotation of the high around a vertical axis (i. e. wrenching) causing transpression on the Polhem Subplatform and transtension in the Swaen Graben and the Loppa High interior.

The cause of uplift of the Loppa High is poorly constrained but was contemporaneous with extreme lithospheric thinning in the Tromsø and Bjørnøya basins in the west. We suggest that isostatic flexuring, thermal heating and/or phase changes at deeper crustal levels are processes

that may have been involved in driving the uplift although these are aspects that need to be further tested.

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Figure captions:

Figure 1: Overview of the study area showing the main structural elements. The extent of the Loppa High is marked in light grey. Location of wells and key seismic lines used in the paper is given, in addition to the location of important structures discussed in the text (see legend for more details) **a)** Detailed structural map of the Polhem Subplatform. **b)** Detailed structural map of the Asterias Fault Complex and associated structures. **c)** Detailed structural map of the Goliat hydrocarbon field area. Structural element map modified from npd.no. FC = Fault Complex

Figure 2: Stratigraphic framework for the Hammerfest Basin and the Polhem Subplatform used in this paper. Note that the lithostratigraphy is only valid for the Hammerfest Basin. Lithostratigraphy and chronostratigraphy from NORLEX (Worsley et al. 1988, Gradstein et al. 2010).

Figure 3: Schematic overview of criteria used for identification of tectonic inversion in this paper. **a)** Typical inversion geometry in an inverted half-graben showing the relationship between rift-related strata being modified by inversion. Black dot shows the position of the null point, which marks the divide between normal displacement below and reverse displacement above. Modified after Turner and Williams (2004). **b)** Sketch of characteristic shapes of deformed fault blocks and deformed fault planes owing to horizontal shortening. **c)** Folding through buckling owing to the localizing of inversion along a pre-existing normal fault. Reverse faults may or may not develop in the sub-strata. **d)** Development of contractional structures such as snake-head folds and footwall cut-offs in syn-rift or post-rift sediments owing to reverse reactivation along a below-lying normal fault.

Figure 4: Uninterpreted and interpreted seismic line running from the Bjarmeland Platform in the southeast, across the Loppa High, Jason Fault Complex and the Polhem Subplatform in the northwest. Names of seismic reflections are given along the left margin of the figure. See Figure 1 for location.

Figure 5: a) Uninterpreted and interpreted seismic line running across the Loppa High, Jason FC, Polhem Subplatform and into the Bjørnøya Basin. b) and c) Details from the same area. Minor arrows indicate onlap. See Figure 1 for location. Color scheme as in Figure 4.

Figure 6: Uninterpreted and interpreted seismic line running across the Hammerfest Basin, from Loppa High in the north to the Finnmark Platform in the south, crossing the Asterias and Troms-Finnmark fault complexes. Minor arrows indicate onlap. See Figure 1 for location.

Figure 7: Uninterpreted and interpreted seismic line showing the major anticline associated with the Goliat hydrocarbon field. Note the minor folds on the crest of the anticline and the onlap geometry (inset). Minor arrows indicate onlap. Names of seismic reflections are given along the left margin of the figure (cf. Fig. 3). See Figure 1 for location.

Figure 8: Table summarizing Cretaceous rift activity in the region together with the constrained time interval for which the described tectonic inversion structures formed. Chronostratigraphy from Gradstein et al (2010).

Figure 9: a) Tectonic model showing how uplift of the Loppa High in the early Barremian to early Aptian may have been converted into horizontal stresses owing to space accommodation problems along its flanks. See Fig. 9c for location and orientation of profiles. b) Graph showing the expected horizontal shortening to uplift ratio as a function of fault dip. White dot represents values for the Asterias Fault Complex. c) Schematic illustration of horizontal stress generated by uplift (red arrows) and resulting horizontal clockwise rotation (grey arrow) due to unbalanced horizontal stresses (red arrows) of the Loppa High. BFC, Bjørnøyrenna Fault Complex.