Extensional Faulting and Folding in Sedimentary Growth Basins: Case Studies from Seismic and Outcrop Data

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Preface

This thesis entitled “*Extensional Faulting and Folding in Sedimentary Growth Basins: Case Studies from Seismic and Outcrop Data*” has been submitted to the Department of Geosciences at the University of Oslo in accordance with the requirements for the degree of Philosophiae Doctor (PhD). The work presented herein was carried out at the University of Oslo (UiO), where the candidate has been enrolled as a PhD Fellow between March 2015 and March 2019, during which time the candidate has had approximately one year accumulated leave.

Financial support for this study was provided by the *Lower Cretaceous Basin Studies in the Arctic (LoCrA)* consortium hosted at the University of Stavanger (UiS). The principal supervisor for this work was Professor Alvar Braathen (UiO) with co-supervision from Professor Jan Inge Faleide (UiO), Associate Professor Ivar Midtkandal (UiO) and Professor Alejandro Escalona Varela (UiS). The work was primarily undertaken at the University of Oslo. Field work was conducted in the Sultanate of Oman during two field seasons (January-February 2017 and November-December 2017).

This thesis displays the results of this three year study, and is structured in two parts. The first section gives an introduction to the geological framework of the study areas. It also provides the necessary scientific background for the results presented in the second section, which constitutes the main body of the thesis. Here, a compilation of three first authored articles is presented. The first manuscript was published in *Marine and Petroleum Geology* in 2017 and the second was published in *Basin Research* in February 2019. The third manuscript was being prepared for submission to *Basin Research* at time of thesis submission. The appendices provide details for additional work undertaken during the PhD study; (i) Two first author conference abstracts (International Meeting of Sedimentology (IMS), Toulouse, 2017; Winter Conference, Norwegian Geological Society, Bergen, 2019), (ii) four co-authored articles (one published, two in press, one in review at the time of thesis submission) and (iii) co-supervision for two MSc students (one finished 2016, one scheduled to finish June 2019).

Christopher Sæbø Serck

Oslo, 1 April 2019

Abstract

This PhD thesis addresses how fault and fold growth affect accommodation development and sediment routing and fill in extensional basins. Extensional basins are key constituents of passive continental passive and intra-continental rift systems and hold great potential accumulation of reservoir-grade successions of sediments. These types of basins differ widely in terms of e.g. fault and fold properties, duration of faulting, accommodation development, tectono-climatic setting and lithology of basin substrate and fill. Accordingly, constructing general models for extensional basin evolution is challenging. Combining different types of datasets that offer different observation scale and resolution can mitigate this.

This thesis presents seismic case studies from the Fingerdjupet Subbasin, southwestern Barents Sea and outcrop studies from the Bandar Jissah Basin, northeastern Oman. Seismic analyses include interpretations of faults and horizons bounding seismic reflector packages; age control was achieved through seismic ties to hydrocarbon exploration wells. Additional insight was gained from analysis of isochore thickness maps and horizon and fault attributes. Outcrop data consists of measured sedimentological sections and structural data that are coupled to a collection of high-resolution photomosaics. Results from both datasets highlight how extensional fault-related folding significantly impacts accommodation evolution and sedimentary architecture. The Fingerdjupet Subbasin evolved as a semi-regional rollover associated with displacement on the Terningen Fault Complex. On a smaller scale, growth of a fault-bend anticline limited deposition near the Terningen East fault, causing sediments to accumulate in a fault-bend syncline further into the hangingwall, away from the fault. The history of fault growth, fault linkage and fold growth in the Fingerdjupet Subbasin is deduced by examining sedimentary architecture. In the Bandar Jissah Basin, rollover folding was set up by displacement along the Banurama detachment, causing drainage diversion and deposition of growth packages on the rollover flank.

Transverse folds reflect lateral fault segmentation and constrain the lateral extent of early syn-rift basins in the Fingerdjupet Subbasin. Transverse fold trajectory analysis determines segmentation and linkage in the fault array that control folding, accommodation distribution, sediment entry points to hangingwall basins and potential trapping structures. The longevity of transverse folds through several phases of vertically decoupled faulting in the Fingerdjupet Subbasin emphasizes the importance of inherited structural fabrics during rifting.

There is a transition from supradetachment basin to rift-style basin setting in the Bandar Jissah Basin that is reflected in a changing accommodation pattern. Displacement on late, steep faults (Marina and Yiti Beach) set up local E-W to N-S proximal-distal trends. This pattern is superimposed onto the regional N-directed accommodation increase that resulted from displacement along an older detachment (Banurama). Additional evidence for a rift-style basin setting include growth packages in the proximal hangingwall of the steep Marina fault, alignment of distinct facies belts to fault strike and reduced

siliciclastic input to hangingwall basins. A similar major structural transition is inferred for the Fingerdjupet Subbasin, where steep basin-bounding faults sole out in a low-angle detachment at depth.

This thesis adds to the general understanding of extensional basins through investigations of basins differing in age, location and tectonic setting. Utilizing different datasets and observation at various scales allows knowledge-building. This work adds to ongoing – and will guide future research on syn-sedimentary faulting and folding in extensional settings.

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First and foremost, I would like to thank my principal supervisor, Professor Alvar Braathen (UiO), for granting me this fantastic PhD opportunity. Your support during these years has helped me grow as a (relatively) young researcher and I have learned a lot from your to-the-point and pragmatic approach to scientific work. I am truly inspired by your work ethic, adventurous spirit and endless motivation for geological discovery. The highlights of my doctoral studies have, without a doubt, been the experiences of visiting and conducting field work in many world-class localities, many times with you as company. I have appreciated our conversations about geology, our families and life in general. I thank my co-supervisor Professor Jan Inge Faleide (UiO) for sharing his vast knowledge about Arctic geology in general and the Barents Shelf in particular. Your knowledge and hunger to learn has been an inspiration to me from the first time we met, several years prior to starting this PhD. I have enjoyed having you as a discussion partner during these years, and your sharp eye for details has been a great help. My bonus co-supervisor, Associate Professor Ivar Midtkandal (UiO); I thank you for the many discussions, field experiences, conferences and hangouts at Blindern and elsewhere. We share the same (bad) humour and I've had a lot of fun being around you. Your door has always been open – this is much appreciated. My co-supervisor Professor Alejandro Escalona Varela (UiS) is acknowledged for setting up the LoCrA project and for support during the initial stages of this PhD project. Professor Snorre Olaussen (UNIS) is thanked for good days at the outcrops in Oman.

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List of articles

Article 1 – Published in Marine and Petroleum Geology

Serck, C. S.¹, Faleide, J. I.^{1,2}, Braathen, A.¹, Kjøllhamar, B.³, & Escalona, A.⁴ (2017). Jurassic to Early Cretaceous basin configuration(s) in the Fingerdjupet Subbasin, SW Barents Sea. *Marine and Petroleum Geology*, 86, 874-891. DOI: <https://doi.org/10.1016/j.marpetgeo.2017.06.044>

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Article 3 – Prepared for submission to Basin Research

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1. Introduction

1.1. Motivation

Understanding extensional basins is a complex exercise that requires a broad approach; explicit knowledge about extensional fault and fold growth linked with accommodation development, drainage evolution and sedimentary architecture rely on the extent, quality and resolution of available datasets. Seismic data are spatially extensive and carry a potential for large-scale correlation of structures and stratigraphic surfaces, but limited sampling and the inherent attenuation of the seismic signal as it travels through the subsurface provide resolution challenges that increase with depth. Outcrop data offers excellent resolution but limited spatial extent. By combining the two approaches, sub-seismic structures and sedimentary architectures described in outcrop data can be used predictively in seismic data interpretation. Seismic data, on the other hand, show a grander perspective that is sometimes lost during field work, especially with limited outcrop availability.

Extensional basins essentially record series of slip events (earthquakes) that cater for sediment accumulation in evolving depocenters. A better understanding of extensional basins advances concepts that can be applied in hydrocarbon and groundwater exploration, CO₂ storage prospecting and geohazard evaluation in areas that are affected by extensional tectonics. Accordingly, studies targeting extensional fault and fold growth with links to sedimentary architecture can have far-reaching impacts for academia, industry and society.

1.2. Aims and objectives

This thesis aims at improving the general understanding of how growth of extensional faults and folds impacts accommodation development and sedimentary architecture in extensional basins. This is achieved by investigating two extensional basins that differ in terms of their tectonic and climatic setting, fault properties and sedimentary fill, utilizing seismic data from the Fingerdjupet Subbasin, SW Barents Sea and outcrop data from the Bandar Jissah Basin, NE Oman.

The first objective is to establish a detailed seismic- and tectonostratigraphic framework for Jurassic to Lower Cretaceous strata in the Fingerdjupet Subbasin, SW Barents Sea and discuss the findings in a regional context. This is achieved by scrutinising seismic-stratigraphic architectures and investigating faults in 3D seismic reflection data. The results of these investigations are presented in **Article 1**.

The second objective is examining how growth of extensional faults and folds affect accommodation evolution and sedimentary infill of rift basins. High-resolution seismic mapping, quantitative throw analysis and the novel technique of transverse fold trajectory analysis are performed to achieve this objective. This study, investigating a large, reactivated normal fault bounding the Fingerdjupet Subbasin is presented in **Article 2**.

The third objective is a structural and sedimentological study of the Paleogene Bandar Jissah Basin, NE Oman. This basin evolved as a consequence of extensional tectonics in the Oman Mountains with onset in the Late Cretaceous. The ramifications of syn-sedimentary fault characteristics and consequent extensional folding on accommodation evolution and mixed carbonate-siliciclastic basin fill are discussed and presented in **Article 3**.

The fourth objective is to distil the main outcomes from the articles presented herein and to discuss extensional basin evolution in general; comparing and contrasting observations from the Fingerdjupet Subbasin and Bandar Jissah Basin. These basins evolved under different tectonic and climatic conditions, with different syn-sedimentary fault characteristics and basin fill lithologies. However, many similarities with respect to basin structure, impact of faulting and folding on accommodation, and sedimentary architecture validate important learning values.

2. Scientific background

This study provides an improved understanding of the growth of extensional faults and fault-related folds, with implications for accommodation evolution, facies distributions and sedimentary stacking in the extensional basins discussed herein. Faults are discontinuities that records displacement of one side relative to the other. Faults grow in increments by lateral propagation of fault tips and displacement accrual, with slip events in most cases recorded as earthquakes. Faults are classified as normal, reverse or strike-slip depending on fault kinematics, which relate to the orientation of the principal stresses leading to faulting (Anderson, 1951). Here, I study extensional basins bounded by normal faults, demonstrating a strong link between fault properties, host-rock deformation, accommodation development and sediment partitioning and fill in hangingwall basins. Understanding faults and fault-related folds is critical in exploration for hydrocarbons and groundwater and evaluation of CO₂ storage prospects in rift basins because:

- Spatial and temporal distribution of potential reservoir and source rocks in rift basins relate to the geomorphology generated by faults and fault-related folds interacting with the free surface.
- Faults may serve as barriers or conduits for fluids and may thus significantly impact prospect volumes.
- Formation of structures suitable for retaining fluids is closely linked with extensional faulting and folding. The timing of trap formation relative to fluid migration in the subsurface is of utmost importance in prospect evaluation.

The articles, manuscripts and conference abstracts presented herein, with observations and interpretations from seismic data in the Fingerdjupet Subbasin in the southwestern Barents Sea and fieldwork in the Bandar Jissah Basin in the Sultanate of Oman, add to the growing body of literature focusing on extensional tectonic settings and rift basin evolution; below follows a summary of relevant classic and recent research articles upon which this thesis builds.

2.1. Fault growth

The time it takes for faults to establish their full length has been a topic of recent discussions. The isolated fault model assumes contemporaneous lateral tip propagation and displacement accrual, while the constant-length model predicts that faults rapidly establish their full length and subsequent fault growth is manifested by displacement accrual with “stationary” lateral fault tips (Walsh and Watterson, 1988; Dawers and Anders, 1995; Mansfield and Cartwright, 2001; Childs *et al.*, 2003, 2017; Giba, Walsh and Nicol, 2012; Jackson and Rotevatn, 2013; Jackson *et al.*, 2017). To attain a certain length, the fault tips of any fault *must* have propagated laterally. Jackson *et al.* (2017) and Rotevatn *et al.* (2018) argue for a hybrid growth, where faults attain their full length during the 20-30% of fault life and subsequently grow by displacement accrual. Lateral fault growth and linkage have consequences for basin size and morphology as well as sediment routing from rift-external sediment sources to hangingwall basins during

early rifting (Rotevatn, Jackson, *et al.*, 2018). If a fault is allowed to propagate freely in the subsurface, the displacement field is circular with maximum displacement in the middle of the circle. Displacement maxima indicate fault nucleation sites. Modifications to the displacement field occur as faults propagate through heterogeneous media with variable rheology (e.g. Rippon, 1984; Wilkins and Gross, 2002). Different mechanical properties of sedimentary strata affect fault propagation, e.g. fault propagation through a stiff stratigraphic layer and fault arrest upon reaching a layer of plastic claystone. Further rejuvenation and propagation occurs within the stiff layer and the displacement field becomes elongated with a flat top at the boundary between the two mechanical layers (Soliva and Benedicto, 2005; Fossen, 2016). Asymmetric displacement fields also relate to 1) kinematic interference with other faults and 2) whether the faults breach the surface (e.g. Morley, 1999; Duffy *et al.*, 2015).

2.2. Relay zones and fault linkage

Relay zones form when two faults propagate to the point where they overlap and displacement is transferred between them (e.g. Childs, Watterson and Walsh, 1995; Kristensen, Childs and Korstgård, 2008; Fossen and Rotevatn, 2016). Faults are soft-linked when the ductile/continuous deformation in the relay zone transfers displacement between the faults without physically linking, and hard-linked/breached when the faults are physically connected. Breaching is facilitated either by propagation of the footwall fault, hangingwall fault, both faults, or by a new breaching fault (Childs, Watterson and Walsh, 1995). Fault linkage reduces the number of faults (fault segments) while increasing average fault length. Relay zones in extensional basins result from lateral propagation of adjacent faults and vertical propagation of faults that have nucleated at different depths (dip linkage), yielding a variety of fault shapes that may induce deformation of the host rock with subsequent displacement. In general, (paleo-)relay zones are associated with displacement minima oriented along dip for lateral relay zones and along strike for vertical relay zones (e.g. Baudon and Cartwright, 2008; Cartwright *et al.*, 1995; Lohr *et al.*, 2008; Mansfield and Cartwright, 1996), but become obscured as displacement accumulates on the fault that formed by hard-linkage of the initial fault segments.

2.3. Fault reactivation and importance of earlier fabric

Previously established tectonic fabrics affect fault growth during subsequent rift phases (Keep and McClay, 1997; Morley *et al.*, 2004; Henza, Withjack and Schlische, 2011; Whipp *et al.*, 2014; Collanega *et al.*, 2018). In multiphase rifts, faults reactivate either by upward propagation of existing faults or by dip linkage, where new faults nucleate in the overburden of old faults before linking through breaching of a vertical relay zone (Baudon and Cartwright, 2008). Pre-existing structures may affect both the length of faults resulting from later phases of extension (Paton, 2006; Giba, Walsh and Nicol, 2012; Jackson and Rotevatn, 2013; Rotevatn and Jackson, 2014; Rotevatn, Kristensen, *et al.*, 2018) and the time it takes to establish final fault length, with great implications for accommodation, drainage development and sediment supply (Henstra *et al.*, 2017). The morphology of hangingwall basins may also be modified by

displacements in the non-planar fault geometries that result from dip linkage (Rotevatn and Jackson, 2014).

2.4. Fault-related folding

Extensional fault-related folding is inherent in any rift basin and result from differential displacement along the length of the fault, host-rock deformation near propagating fault tips or displacement in non-planar fault geometries (e.g. Hamblin, 1965; McClay and Scott, 1991; Xiao and Suppe, 1992; Schlische, 1995; Janecke, Vandenburg and Blankenau, 1998; Mauduit and Brun, 1998; Corfield and Sharp, 2000; Khalil and McClay, 2002; Rotevatn and Jackson, 2014). Extensional folding can have a strong influence on geomorphology in rift basins, modifying accommodation, drainage patterns and sedimentary stacking (e.g. Schlische and Olsen, 1990; Schlische, 1995; Gawthorpe *et al.*, 1997; Gawthorpe and Leeder, 2000; Sharp *et al.*, 2000; Withjack, Schlische and Olsen, 2002; Jackson, Gawthorpe and Sharp, 2006; Wilson *et al.*, 2009). Folds with fault-parallel hinges include 1) fault-tip monoclines above propagating fault tips. Breaching of fault tip monoclines have been suggested to be principal mechanism for the formation of drag folds (Schlische, 1995; Khalil and McClay, 2002; Jackson, Gawthorpe and Sharp, 2006). 2) Reverse-drag folds, which are responses to displacement decrease away from faults and affect both the footwall and hangingwall sides of the faults (Barnett *et al.*, 1987; Schlische, 1995). 3) Fault-bend folds, including rollover folds, which relate to displacement on listric or non-planar faults (Xiao and Suppe, 1992; Rotevatn and Jackson, 2014). Fault-bend folds also include more complicated fold sets depending on fault geometry. Folds with hinges perpendicular to fault strike (transverse folds) form mainly as a response to differential displacement along the length of a fault. For single faults, broad hangingwall transverse synclines plunge towards the fault at the location of maximum subsidence while footwall anticlines plunge away from the fault, located behind the fault at the position of maximum footwall uplift (Schlische, 1995). The fold amplitude is dependent on the relationship between fault length and displacement. In the hangingwall of segmented fault systems the transverse synclines related to maximum displacement for each fault segment are separated by transverse anticlines located at relay zones, which represents a displacement minimum for both segments (Schlische, 1995). These displacement minima may persist even after fault linkage and subsequent displacement in the linked fault system (Morley, 2002). Transverse folds may also result from dip-oriented undulations in the fault surface, producing anticlines at salients and synclines at recesses (Schlische, 1995; Janecke, Vandenburg and Blankenau, 1998).

2.5. Rift basins

During a single rift phase, fault arrays go through several more or less distinct stages, which are reflected in the sedimentary record of the resulting rift basins (Prosser, 1993; Gupta *et al.*, 1998; McLeod *et al.*, 2002; Leppard and Gawthorpe, 2006; Gabrielsen, 2015). The fault initiation stage, fault intersection and linkage stage, and through-going fault stage record strain localization from many small faults to fewer, larger faults (Cowie, Gupta and Dawers, 2000; Gawthorpe and Leeder, 2000). In multi-phase rift basins

these stages are repeated for each rift phase, although it has been suggested that the development towards the through-going fault stage is accelerated by reactivation of the previously established through-going faults (Ravnås *et al.*, 2000; Whipp *et al.*, 2014; Henstra *et al.*, 2017). A pronounced increase in subsidence rates is common as strain is localized to fewer faults during the later stages of a rift phase, commonly leading to sediment starvation of hangingwall basins (Prosser, 1993; Gupta *et al.*, 1998; McLeod *et al.*, 2002; Leppard and Gawthorpe, 2006). The sedimentary stacking and degree to which rift basins are filled, however, result from many factors. Sediment yield potential of hinterland drainage catchments, amplified by climate, exerts important control on the degree to which a basin becomes starved, underfilled, balanced or overfilled. Yield potential of rift-interior sediment sources whose relief is enhanced by normal faulting is highly variable with key factors including climate and the size and gradient of subaerially exposed parts of the rift system. Additionally, prerift substrate (durability of uncovered rocks) is paramount for the timing of significant sediment delivery to evolving rift basins and may help explain why different rift basins display very different sedimentary signatures for the same rift stages (Prosser, 1993; Ravnås and Steel, 1998). Duration of subaerial exposure, which again relate to eustasy and prerift topography and bathymetry, is also important for development of effective drainage networks. The relative sea level during rifting influences sediment production from rift-interior sources and development of important stratal surfaces; while uplifted footwall highs develop erosion surfaces in continental or marginal marine rift basins, non-deposition or condensation on footwall highs is more typical in fully submerged rift basins (Ravnås and Steel, 1998; Withjack, Schlische and Olsen, 2002). The stratigraphic record of rift basins may show widely different depositional settings from proximal alluvial fan deposits to shallow marine carbonates and deep-marine (hemi)pelagic deposits (Prosser, 1993; Ravnås and Steel, 1997; McLeod *et al.*, 2002; Henstra *et al.*, 2016). Faulting controls accommodation development and the architecture of sedimentary packages in rift basins; packages may thicken towards the controlling fault if it breaches the surface or away from the fault if it is blind and propagate upward in the subsurface, setting up an extensional fault-tip monocline (Gawthorpe *et al.*, 1997).

2.6. Supradetachment basins

In contrast to rift basins, which are characterized by steep faults, supradetachment basins develop in the hangingwall of low-angle detachments, and these two basin types represent end-member extensional basins (Friedmann and Burbank, 1995). While rift basins are bounded by faults steeper than 45°, have low extension rates and beta factors around 1.2, supradetachment basins are bounded by low-angle faults, have high extension rates and beta factors of ~1.5-4. Supradetachment basins involve the whole crust in wide areas and accommodate significant crustal thinning, isostatically compensated by exhumation of metamorphic core complexes (Lister and Davis, 1989; Friedmann and Burbank, 1995; van Hinsbergen and Meulenkamp, 2006). This uplift limits accommodation near the detachment in the hangingwall basin and generates large, high-relief catchment areas from which dominantly transverse drainages transport coarse-grained sediments to depocenters distal with respect to the detachment (Davies and Warren, 1988; Friedmann and Burbank, 1995; Oner and Dilek, 2011). It is emphasized that

rift basins and supradetachment basins are end-members and that extensional basins can display characteristics of both. Extensional basins may also develop different characteristics over time, for instance as the detachment rotates during uplift from unroofing (e.g. Braathen and Osmundsen, submitted; Platt, Behr and Cooper, 2015). Furthermore, rift-style basin characteristics can dominate the upper plate in detachment fault settings (e.g. Friedmann and Burbank, 1995; Brun *et al.*, 2018).

3. Geological Context

Articles 1 and 2 discuss the interaction between extensional tectonics and sediment distribution based on seismic data from the Fingerdjupet Subbasin in the southwestern Barents Sea. Article 3 builds on field data from the Bandar Jissah Basin in Oman, undertaken as an analogue study to Barents Sea rift basins. The Fingerdjupet Subbasin and Bandar Jissah Basin both record syn-tectonic deposition in depocenters where displacement on basin-bounding fault complexes drives accommodation. They are presented separately in this section due to their location, age and lithologies.

3.1. Fingerdjupet Subbasin, southwestern Barents Sea

The Barents shelf represents the northwestern corner of the Eurasian plate, covering the expanse between the Norwegian-Greenland Sea to the west, the Arctic ocean to the north, Novaya Zemlya to the East and mainland Norway and Russia to the south (Fig. 1) (Faleide *et al.*, 2008; Smelror *et al.*, 2009). The current Barents shelf is seen as the result of a string of initially contractional and later extensional tectonics events reflecting continent assembly and breakup (Faleide, E. Vågnes and Gudlaugsson, 1993; Faleide *et al.*, 1996; Gudlaugsson *et al.*, 1998). The north-trending Fingerdjupet Subbasin is located southeast of Bjørnøya, surrounded by the Bjørnøya Basin to the west, Bjarmeland Platform to the east and Loppa High to the south (Fig. 2) (Gabrielsen *et al.*, 1990).

Fig. 1: Study areas. Satellite image courtesy of Google Earth.

Fig. 2: Fingerdjupet Subbasin overview (modified from Article 1 & 2). *a*) The southwestern Barents Sea in the Arctic (modified from Jakobsson *et al.*, 2012). *b*) Southwestern Barents Sea basins and highs (modified from Faleide, Bjørlykke and Gabrielsen, 2015). Abbreviations: BB – Bjørnøya Basin, FSB – Fingerdjupet Subbasin, SH – Stappen High. *c*) Near Base Cretaceous depth structure map. *d*) Interpreted seismic line showing structural elements of the study area. Seismic line location shown in *c*). Seismic data courtesy of TGS.

The Caledonian orogeny reflects the collision between Laurentia and Baltica in the Silurian to Early Devonian, and the resulting rock assembly forms the basement of the study area (Doré, 1991; Ritzmann and Faleide, 2007; Gernigon and Brönnner, 2012). Extensional collapse in the Barents Sea Caledonides and extensional reactivation have been inferred from magnetic data analysis in the southwestern Barents Sea (Gernigon and Brönnner, 2012), from seismic (OBS and streamer) and potential field data in the northwestern Barents Sea (Gudlaugsson and Faleide, 1994; Breivik *et al.*, 2002, 2005; Ritzmann and Faleide, 2007) and based in field work on Bjørnøya (Braathen *et al.*, 1999). Recent accounts on late/post-Caledonian extension of northern Norway and north Svalbard offers a broader basis for discussions on basement configurations (Braathen *et al.*, 2018; Davids *et al.*, 2018; Koehl *et al.*, 2018). An east-dipping detachment in the Fingerdjupet Subbasin was described by Gudlaugsson *et al.* (1998). Although tectonic inversion of extensional fault systems have been reported (Gabrielsen, Grunnaleite and Rasmussen, 1997; Faleide *et al.*, 2008; Indrevær, Gabrielsen and Faleide, 2017), the post-Caledonian evolution of the southwestern Barents shelf is dominated by at least five phases of extensional faulting (Faleide, E. Vågnes and Gudlaugsson, 1993; Gudlaugsson *et al.*, 1998; Glørstad-Clark, 2011; Clark *et al.*, 2014). The area endured extensional faulting events in the mid-late Carboniferous, late Permian-Early Triassic, Middle Jurassic-Early Cretaceous and Late Cretaceous-Cenozoic in addition to Late Devonian extensional collapse.

Mid-late Carboniferous rifting partitioned the Barents Shelf into several basins and highs (Fig. 2b). The Nordkapp, Maud, Bjørnøya, Ottar and Tromsø basins were mainly filled with siliciclastic deposits but also some evaporites during mid-late Carboniferous (Gudlaugsson *et al.*, 1998; Faleide, Bjørlykke and Gabrielsen, 2015). The Bjørnøya Basin, Fingerdjupet Subbasin and Stappen High (paleo-basin) have been inferred to initiate as rift basins during this period on the basis of seismic observations of such features as sedimentary growth packages and salt diapirs (Dengo and Røssland, 1992; Breivik, Faleide and Gudlaugsson, 1998; Gudlaugsson *et al.*, 1998; Blaich, Tsikalas and Faleide, 2017).

The mid-late Carboniferous synrift strata were covered by an uppermost Carboniferous to lower Permian regional carbonate platform deposits (Larssen *et al.*, 2002; Henriksen, Ryseth, *et al.*, 2011; Faleide, Bjørlykke and Gabrielsen, 2015). A new rift event affected the western Barents Sea from the Late Permian to Early Triassic, discussed by Gudlaugsson *et al.* (1998) and conformed to later through analysis of improved seismic data in the Bjørnøya Basin, Fingerdjupet Subbasin and southern Stappen High (Fig. 2d) (Glørstad-Clark, 2011; Faleide, Bjørlykke and Gabrielsen, 2015; Kamp, 2016; Blaich, Tsikalas and Faleide, 2017).

The Barents Sea, including the Fingerdjupet Subbasin, was an underfilled, epicontinental basin during the Early to Middle Triassic. A SW-sourced shoreline to coastal plain succession filled the areas towards the latest Triassic being (Glørstad-Clark *et al.*, 2010). Kamp (2016) described Upper Triassic growth packages on N-S to NNE-SSW striking faults in the Fingerdjupet Subbasin, indicating Late Triassic fault reactivation. In the Hammerfest Basin and on Edgeøya and Hopen (islands), south and north on the

Barents Shelf, respectively, E-W striking faults were active in the latest Triassic (Anell *et al.*, 2013; Osmundsen *et al.*, 2014; Anell, Faleide and Braathen, 2016; Mulrooney, Leutscher and Braathen, 2017; Ogata *et al.*, 2018).

Extensional faulting from the Rockall Trough west of Ireland to the Barents Sea during the Middle to Late Jurassic resulted in a regional rift basin (Faleide, E. Vågnes and Gudlaugsson, 1993). Rifting in both the North Atlantic and Arctic (Amerasia Basin) regions affected structuring of the southwestern Barents Sea at this time. In the Hammerfest Basin, rifting culminated in the Late Jurassic to earliest Cretaceous, and this rift phase also affected the Bjørnøya Basin and southern Stappen High through fault reactivation (Faleide, E. Vågnes and Gudlaugsson, 1993; Blaiçh, Tsikalas and Faleide, 2017). In the early Barremian, displacement in E-W striking faults in the Hammerfest Basin had ceased, and the Loppa High was uplifted, leading to inversion of its flanking faults, subaerial exposure and erosion (Indrevær, Gabrielsen and Faleide, 2017).

North Atlantic tectonism affected the study area increasingly through the Early Cretaceous, likely forming and/or rejuvenating major fault complexes and causing rapid subsidence in the Bjørnøya Basin (Fig. 2d) (Faleide, E. Vågnes and Gudlaugsson, 1993). Growth packages in the Bjørnøya Basin and erosional truncation of the high between the Bjørnøya Basin and Fingerdjupet Subbasin reflect surface-breaching faulting at this time (Fig. 2d) (Faleide, E. Vågnes and Gudlaugsson, 1993).

Regional uplift related to magmatism in the High Arctic Large Igneous Province (HALIP, ~125 Ma) caused subaerial exposure and sediment shedding from the northern Barents margin (Corfu *et al.*, 2013; Senger *et al.*, 2014; Polteau *et al.*, 2016). This was manifested in large deltaic complexes prograding southeast past Svalbard to the southwestern Barents Sea (Midtkandal *et al.*, no date; Faleide, E. Vågnes and Gudlaugsson, 1993; Midtkandal and Nystuen, 2009; Faleide, Bjørlykke and Gabrielsen, 2015; Grundvåg *et al.*, 2017; Marín *et al.*, 2017). Field data and seismic- and magnetic data from the northern Barents shelf suggest magmatic features dominantly trend NNE, similar to basin-bounding faults in the Fingerdjupet Subbasin (Grogan *et al.*, 2000; Minakov *et al.*, 2012). Mesozoic extension in the Bjørnøya Basin and southern Stappen High culminated in the Aptian (Fig. 2d) (Faleide, E. Vågnes and Gudlaugsson, 1993; Blaiçh, Tsikalas and Faleide, 2017). Subsidence and infill of the Bjørnøya Basin continued after Aptian faulting ceased (Faleide, E. Vågnes and Gudlaugsson, 1993; Faleide, Erling Vågnes and Gudlaugsson, 1993).

Late Cretaceous to Paleogene extension eventually led to breakup and seafloor spreading in the Norwegian-Greenland Sea in the Early Eocene, forming narrow basins along the western Barents Sea margin and northeast Greenland in response to regional shear (Faleide *et al.*, 2008; Svennevig, Guarnieri and Stemmerik, 2017). The Barents margin is segmented, causing a variety of structural settings along its length. The southern margin segment is sheared (Senja Fracture Zone), the central margin southwest of Bjørnøya is rifted with extensive volcanism, and the northern (Svalbard) margin is sheared and later rifted

(Gabrielsen, Grunnaleite and Rasmussen, 1997; Vågnes, Gabrielsen and Haremo, 1998; Braathen *et al.*, 1999; Faleide *et al.*, 2008; Faleide, Bjørlykke and Gabrielsen, 2015; Indrevær, Gabrielsen and Faleide, 2017; Kristensen *et al.*, 2017).

Significant uplift and erosion of the Barents Shelf took place during the Neogene, leading to removal of post-Early Cretaceous strata from the Fingerdjupet Subbasin (1600-2600 m uplift). The uplift left an erosional gap between Bjørnøya and Svalbard, making direct onshore-offshore correlations of Early Cretaceous depositional systems unattainable (Faleide *et al.*, 1996; Dimakis *et al.*, 1998; Henriksen, Bjørnseth, *et al.*, 2011; Baig *et al.*, 2016).

3.2. Bandar Jissah Basin, northeastern Oman

The Bandar Jissah Basin of northeastern Oman occupies a position between the shoreline of the Gulf of Oman and the Oman Mountains (Fig. 3). Rocks exposed in the Oman Mountains represent the remnants of a Late Cretaceous obduction orogeny, where an assemblage of Permian to Upper Cretaceous sedimentary strata and volcanics were thrust southwards onto the Arabian Neo-Tethys Margin (Glennie *et al.*, 1973, 1974; Lippard, Shelton and Gass, 1986; Searle, 2007; Cooper, Ali and Searle, 2014; Rollinson *et al.*, 2014). Thrust stacking in the northern hinterland was matched by a foreland basin system in the south, offering a sedimentary record of ophiolite emplacement, which ended in the Maastrichtian. The Semail Ophiolite complex, currently outcropping extensively in the Oman Mountains and representing the substrate for the Bandar Jissah Basin, is the most well-studied ophiolite complex of the world (Rollinson *et al.*, 2014). Following obduction of the Semail ophiolite and associated nappe stack the orogeny responded to extensional tectonics. Extension is inferred by currently outcropping high-grade metamorphic rocks, which have been exhumed from depths larger than 30 km in tectonic windows of the Oman Mountains (Boudier, Michard and André Michard, 1981). The late/post-obduction extensional orogeny shed large volumes of sediments to the surrounding areas, resulting in deposition of fan-delta conglomerates onto the Semail Ophiolite in the NE during the Late Campanian to Maastrichtian (Mann, Hanna and Nolan, 1990; Nolan *et al.*, 1990). Active exhumation of regional metamorphic core complexes, where Jabal Akhdar and Saih Hatat represent the two main core complex culminations (Fig. 3a), resulted from orogen collapse and is reflected in the stratigraphy of the Al Khawd Formation. This formation displays an inverse Saih Hatat window stratigraphy, with clast material from the structurally highest thrust nappes deposited at the base of the formation, succeeded by sediment derived from progressively lower levels in the nappe stack (Nolan *et al.*, 1990).

Fig. 3: Bandar Jissah Basin overview (modified from Article 3). a) Northeast Oman overview. b) Overview of the larger study area with key structural elements. Location annotated in a). Satellite photos courtesy of Bing/Microsoft.

Several phases of post-orogenic extensional faulting from the Late Cretaceous to the Eocene have been interpreted based on field data (Mann, Hanna and Nolan, 1990; Fournier *et al.*, 2006) and seismic data offshore N Oman (White and Ross, 1979; Ricateau and Riche, 1980; Mann, Hanna and Nolan, 1990). Extensional faulting controlled post-orogenic accommodation development around the Oman Mountains, giving rise to high-frequency lateral variations of sedimentary facies and thickness (Mann, Hanna and Nolan, 1990; Nolan *et al.*, 1990). Sedimentary rocks of the Jafnayn, Rusayl and Seeb formations outcrop in the Bandar Jissah Basin (Fig. 3b). The Paleocene to Eocene Jafnayn and Rusayl formations were deposited around the Saih Hatat window, onto which the formations thin and onlap, thus emphasizing the topographic prominence of Saih Hatat at this time (Searle, 2007). The Jafnayn Formation unconformably overlies Upper Cretaceous strata or, in the case of the Bandar Jissah Basin, the Semail Ophiolite and consists of varied deposits from continental conglomerates to open-shelf carbonates (Nolan *et al.*, 1990; Racey, 1995; Fournier *et al.*, 2006; Özcan *et al.*, 2015; Haynes, Racey and Whittaker, 2018). The Rusayl Formation consists of lagoonal to offshore transition limestones (Nolan *et al.*, 1990; Racey, 1995; Beavington-Penney, Wright and Racey, 2006; Dill *et al.*, 2007; Özcan *et al.*, 2015). The Lutetian-Barthonian Seeb Formation has been interpreted as an open-shelf carbonate with little terrigenous input and few evidences for subaerial exposure; it has thus been suggested that the Saih Hatat window was submerged by mid-Eocene (Skelton, Nolan and Scott, 1990; Hansman *et al.*, 2017). This implies post-mid Eocene uplift of the Oman Mountains to their current elevation (up to 3 km a.s.l.). The precise timing and cause of the uplift is debated; suggestions for timing range from late Eocene to Oligocene (Würsten *et al.*, 1991; Mount, Crawford and Bergman, 1998; Gray *et al.*, 2006; Saddiqi *et al.*, 2006; Hansman *et al.*, 2017). Uplift mechanisms include far-field compression from the Zagros collision and crustal thickening caused by retardation of Makran subduction, transferring stresses from the Arabia-Eurasia convergence to

northern Oman (Glennie *et al.*, 1974; Nolan *et al.*, 1990; Fournier *et al.*, 2006; Ali and Watts, 2009; Searle and Ali, 2009; Hansman *et al.*, 2017).

4. Data and methods

The articles presented in this thesis are based on a variety of datasets and methods including seismic data interpretation, well log analysis, and outcrop and thin section studies. **Articles 1 & 2** are seismic studies of the Fingerdjupet Subbasin, SW Barents Sea while **Article 3** is an analogue study based on structural and sedimentological field work in the Bandar Jissah Basin, NE Oman. A brief introduction to the datasets and methods used for this thesis is presented below. For more detailed descriptions the reader is referred to the individual articles.

The cornerstone dataset for **Articles 1 & 2** is the 8600 km² 3D seismic survey HF13 acquired by TGS in 2013 utilizing ten 6000 m streamers with a 75 m streamer separation and 7000 ms record length. This dataset provides excellent imaging of Lower Cretaceous to Devonian(?) strata down to more than 10 km depth. TGS' NBR long-offset 2D dataset supplemented the 3D data, and provided links to wireline logs from the exploration wells 7321/7-1, 7321/8-1 and 7321/9-1. In addition to hydrocarbon wells, Sintef's shallow stratigraphic borehole 7320/3-U-1 was investigated in attempts to constrain the ages of interpreted seismic surfaces. Seismic fault and horizon interpretations, horizon attribute analyses and isochore thickness analyses were carried out using Schlumberger's Petrel and DownUnder Geosolutions' Insight software packages. **Article 2** presents fault attributes (dip, strike, throw) and throw-length (T-X) plots that were computed using Badley's T7 (TrapTester) software. Throw-depth (T-Z) and Expansion Index (EI) plots were computed from horizon cutoff readings and isochore thickness maps created using DownUnder Geosolutions' Insight Software. A schematic illustration of the T-X, T-Z and EI plot workflow is presented in Fig. 4. Near-fault deformation was accounted for by projecting horizons towards the fault based on the hangingwall dip trend.

Article 2 presents a new method of assessing transverse folds and their relation to sedimentary growth sections. By selecting either vertical seismic sections picked along strike in the immediate hangingwall of the investigated fault, or by mimicking the fault surface and shifting this into the hangingwall of the fault, a good image of transverse folds is obtained (Fig. 5). These seismic sections are used to pick *transverse fold trajectories* that offer characteristics that can be linked to fault properties and basin fill during rifting. For more details the reader is referred to **Article 2**.

Article 3 is based on field work in the Bandar Jissah Basin, NE Oman, undertaken as an analogue study to the Fingerdjupet Subbasin. A substantial structural and sedimentological dataset was collected over two field seasons in January and December 2017. 21 sedimentological sections accumulating to a total of ~ 2 km were measured in the Paleogene Jafnayn, Rusayl and Seeb Fms, including a substantial amount of paleocurrent measurements. Conventional facies analysis brings about depositional process interpretations. Facies are grouped in facies associations which allow for interpretation of depositional environments. Structural data include measurements of fault strike and dip, trend and plunge of

slickenlines and stretching lineations. High-resolution photomosaics helping correlation of strata across km-scale exposures and were produced using Microsoft's Image Composite Editor.

Fig. 4: Plots based on fault throw.

Fig. 5: Transverse fold trajectory analysis. No scaling implied.

5. Article summaries, authorship and contribution

5.1. Article 1: Jurassic to Early Cretaceous basin configuration(s) in the Fingerdjupet Subbasin, SW Barents Sea

Key words: Tectonics, Fingerdjupet Subbasin, Barents Sea, extensional faulting events, growth packages

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Data processing and interpretation	Serck, Faleide, Braathen, Kjølhamar, Escalona
Approximate contribution	Serck: 80 %; Faleide: 10 %; Braathen: 5 %; Kjølhamar, Escalona: 5 %
Status of the manuscript	Published in <i>Marine and Petroleum Geology</i>

The first article in this collection is based on detailed seismic interpretation of faults and horizons in the Fingerdjupet Subbasin, southwestern Barents Sea with a special emphasis on Lower Cretaceous strata. This is the first published study utilizing 3D seismic data in the Fingerdjupet Subbasin. While the evolution of the Fingerdjupet Subbasin has been discussed previously (e.g. Breivik et al., 1998; Faleide et al., 1993a, 1993b; Gabrielsen et al., 1990; Rønnevik and Jacobsen, 1984), the high-quality 3D seismic dataset HF13, acquired by TGS in 2013 and used for this study, offers an opportunity for high-resolution seismic interpretation to establish a seismic stratigraphic framework that improves the constraints on basin evolution (Fig. 6 and 7).

The article identifies three main fault populations. The first population strikes N-S to NNE-SSW. Faults within this population affect the full basin stratigraphy from Quaternary to acoustic basement. The largest faults in this population have accrued several kilometres of displacement and constitute boundaries between the main depocenters and highs in the study area. An affiliation with growth packages in several stratigraphic levels emphasizes the importance of fault reactivations for basin evolution. The second fault population strikes E-W and offsets mainly Late Triassic to Lower Cretaceous strata. The third fault population strikes NW-SE with fault throws near seismic resolution.

In this article, three structural elements within the study area are defined and given new names that have subsequently been accepted by the *Norwegian Committee on Stratigraphy*. These are the 1) Ringsel Ridge, forming a structural high between the Fingerdjupet Subbasin and Bjørnøya Basin, 2) Terningen Fault Complex, representing the boundary between the Ringsel Ridge and Fingerdjupet Subbasin, and paramount for its evolution, and 3) Randi Fault Set, which marks the transition between the Fingerdjupet Subbasin and Bjarmeland Platform (Fig. 6).

The first article emphasise Jurassic to Early Cretaceous basin development, but the excellent deep seismic imaging calls for a short discussion on earlier basin evolution. The principal fault in the east-facing Terningen Fault Complex sole out in a gently dipping detachment fault, likely representing a reactivated Caledonian thrust fabric. The resulting fault geometry set up a basin-scale rollover into the Terningen Fault Complex, controlling basin development through a series of reactivations. The location, geometry and down-section fault terminations suggest the Randi Fault Set developed as a result of volumetric problems with crestal collapse in the hinge of the rollover anticline (Fig. 6). Prior to the Early Cretaceous, the Terningen Fault Complex accommodated extension in the Carboniferous and Late Permian-Early Triassic with deposition of thick growth wedges (Fig. 8). The E-W fault population is affiliated with latest Triassic to Middle Jurassic growth wedges (Fig. 8). Early Cretaceous reactivations in the N-E to NNE-SSW Terningen Fault Complex led to deposition of growth strata during two discrete periods punctuated by a period of tectonic quiescence; first from the latest Jurassic to Hauterivian and then in the Aptian to early Albian (Fig. 8 and 9). Deltaic deposits derived from a source area NW of Svalbard filled the remnant rift bathymetry during the intermittent period of tectonic quiescence in the Barremian before prograding further southeast onto the Bjarmeland Platform. Detailed seismic interpretations linked with biostratigraphic information in exploration well 7321/7-1 allows for construction of a seismic stratigraphic framework for the Late Triassic to Early Cretaceous Fingerdjupet Subbasin (Fig. 7).

This article has implications beyond the Fingerdjupet Subbasin, contributing to a more complete understanding of the Barents Shelf as summarized below.

1. The inferred extensional reactivation of a Caledonian contractional fabric agrees with observations from Bjørnøya (Braathen et al., 1999), approximately 50 km NW of the study area.
2. The latest Triassic to Middle Jurassic age for E-W striking faults overlaps ages given for similar fault populations on Edgeøya and Hopen in the northern Barents Sea (Osmundsen et al., 2014) and in the Hammerfest Basin offshore Finnmark (Mulrooney et al., 2017), thus accentuating the significance of a hitherto poorly understood extensional faulting event affecting the Barents Shelf.
3. The relatively shallow current burial depth of Lower Cretaceous strata in the Fingerdjupet Subbasin caters for both high-resolution imaging and preservation of relevant stratigraphy, potentially adding to the understanding of the more deeply buried Bjørnøya Basin and the more deeply eroded Bjarmeland Platform, respectively.

- Observations of steeply dipping, northwest prograding clinoforms in the study area contrasts the southeast prograding system described in e.g. Marín et al. (2017) and lends support to Early Barremian uplift and erosion of the Loppa High as suggested by Indrevær et al. (2017).

Fig. 6: Composite seismic profile showing the main structural elements of the study area and adjacent region. Major structures are; from E to W; Hoop Fault Complex, Bjarmeland Platform, Randi Fault Set, Fingerdjupet Subbasin, Terningen Fault Complex, Ringsel Ridge, Leirdjupet Fault Complex and Bjørnøya Basin. Dotted lines indicate changes in seismic line direction and boundaries between different seismic datasets. Inset shows seismic line location (blue), study area (red) and 3D seismic outline (green). Figure modified from **Article 1**. Seismic data courtesy of TGS.

Fig. 7: Seismic stratigraphic framework of the Late Triassic to Albian succession of the Fingerdjupet Subbasin. The Jurassic and Cretaceous basin evolution is the main focus of the present work and for the Norian to Middle Jurassic (~218-168 Ma), which in the study area corresponds to a relatively thin sedimentary package, is therefore hidden in the chronostratigraphy column. Chronostratigraphic chart modified from Gradstein et al. (2012).

Fig. 8: Time thickness maps and seismic sections for sequences 1, 2, 3, 4, 5A and 5B. Wedge-shaped seismic packages consistent with syn-tectonic deposition are seen for sequences 1 (Intra lower Norian – Oxfordian-Callovian), 3 (Berriasian-Tithonian – intra upper Hauterivian) and 5 (Intra Barremian – intra lower Albian). Red arrows indicate thickness variations for the sequences. Seismic profile locations are indicated in the respective time thickness maps. Seismic data courtesy of TGS.

Fig. 9: Seismic profile showing the Triassic to Lower Cretaceous succession of the Fingerdjupet Subbasin. Colour overlays correspond to interpreted sequences as outlined in Fig. 7. Wedge-shaped seismic packages and pronounced thickness differences between the Fingerdjupet Subbasin and the Ringsel Ridge are seen for sequences 3 (BT – iuH) and 5 (iB – iA). The strong, cross-cutting reflections seen in the upper part of the section, particularly near the Ringsel Ridge, are NW-SE oriented faults cut along strike by the seismic profile. Seismic data courtesy of TGS.

5.2. Article 2: Extensional fault and fold growth: impact on accommodation evolution and sedimentary infill

Key words: normal faults, extensional folds, rift basins, tectonics and sedimentation, reactivation, transverse fold trajectories

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The second article in this collection discuss the links between extensional faulting and fault-related folding, accommodation development and sedimentary infill of rift basins, based on 3D seismic data from the Fingerdjupet Subbasin, southwestern Barents Sea. This article adds to the growing body of literature on fault growth, extensional folding and rift basin evolution by targeting a single, yet complex fault in the Terningen Fault Complex. The Terningen East fault marks the boundary between the Fingerdjupet Subbasin and the Ringsel Ridge. The Fingerdjupet Subbasin is a multi-phase rift basin, where the main depocenter developed in the hangingwall of the Terningen East fault between the Devonian and Early Cretaceous.

The interplay between accommodation evolution, drainage and depositional processes during rifting have seen much attention over the last decades (e.g. Schlische & Olsen, 1990; Prosser, 1993; Gawthorpe et al., 1994; Gupta et al., 1998; Ravnås & Steel, 1998; Cowie et al., 2000; Gawthorpe & Leeder, 2000; McLeod et al., 2002; Leppard & Gawthorpe, 2006; Baudon & Cartwright, 2008; Henza et al., 2011). Depending on parameters relating to fault nucleation, growth, shape and interaction with neighboring fault systems, extensional faulting may result in a variety of fold styles that affect surface morphology and thus accommodation magnitude and location, sedimentary pathways and sedimentary stacking patterns (Hamblin, 1965; Schlische, 1995; Gawthorpe et al., 1997; Janecke et al., 1998; Corfield & Sharp, 2000; Gawthorpe & Leeder, 2000; Sharp et al., 2000; Withjack et al., 2002; Rotevatn & Jackson, 2014). Article 2 outlines four different architectures of growth packages in the Fingerdjupet Subbasin based on fault-

perpendicular seismic sections (Fig. 10): i) Growth packages showing stratal divergence towards planar, surface-breaching faults, ii) Fault-tip monocline growth packages, where strata diverge away from normal faults that propagate in the subsurface, generating extensional fault-tip monoclines. Maximum accommodation is thus generated some distance away from the fault. iii) Rollover growth packages, where rollover folding is driven by displacement in listric faults, the upper listric segment (ramp-flat) in a ramp-flat-ramp fault system or a vertically segmented fault where a steep upper segment soles out in a gentler lower segment. iv) Fault-bend syncline growth packages are deposited outboard of fault-bend anticlines, which are the results of displacement in ramp-flat-ramp fault geometries. The along-fault extents of depocenters are guided by fault-perpendicular (transverse) folds.

Differential displacement in laterally segmented fault systems give rise to fault-perpendicular (transverse) folding, which guides the accommodation development along fault systems. Transverse folds are observed from basin-scale (10's of km's) to km-scale perturbations on this trend. Certain transverse folds display a remarkable persistence; Article 2 documents a particular transverse anticline (fault segment boundary) remained stationary during four rift phases from the Carboniferous to Early Cretaceous. This is even more remarkable considering three of the rift phases are characterized by nucleation and growth of new faults in the overburden of previously established fault systems prior to dip linkage, demonstrating the significance of previously established fault fabrics during later rift episodes (Fig. 11).

Article 2 presents a novel approach to transverse fold analysis. Transverse fold trajectories are constructed by tracing the hinges of transverse synclines and anticlines on seismic sections that mimic the fault shape but are shifted into the hangingwall; the characteristics of the trajectories give information about fault segmentation and linkage, accommodation generation, rift-transverse sedimentary routing and the locations of potential targets for hydrocarbon exploration or CO₂ storage (Fig. 12b). Article 2 documents a robust relationship between local and global displacement maxima and transverse folds of various wavelengths (Fig. 13).

Article 2 describes how linkage of fault systems may give fault geometries that cater for fault-bend folding, with great implications for accommodation development and the location and architecture of syn-rift strata. Dip linkage of Permian and Cretaceous fault systems during the Aptian resulted in a ramp-flat-ramp fault geometry leading to fault-bend folding that affected the surface morphology by limiting accommodation close to the surface-breaching fault (Fig. 14). Accordingly, the sediments were deposited in a fault-bend syncline basin outboard of the fault-bend anticline, which itself experienced subaerial exposure and intraformational truncation of the growth wedge. The growth wedges above and below the fault-bend syncline growth package both show stratal divergence towards the fault, thus informing the timing and nature of fault linkage, fold growth and fault shape modifications causing the cessation of fold growth.

Fig. 10: Four main growth basin geometries are described from seismic sections in the study area: (a) Growth packages related to planar surface-breaching faults. (b) Growth package on flank of extensional fault-tip monocline. (c) Rollover basins caused by displacement on listric faults, the upper ramp-flat segment of a ramp-flat-ramp fault or segmented fault systems with steep upper segments and gentler lower segments. (d) Fault-bend synclinal basins related to displacement on a ramp-flat-ramp fault. (e) Transverse growth basins are observed on seismic sections oriented along strike to the fault. Accommodation is generated in fault-displacement synclines that may determine the fault-parallel extent of the growth basins described above. Seismic data courtesy of TGS.

Fig. 11: Various fault attributes have been calculated and projected onto the interpreted 3D fault surfaces to inform fault evolution in time and space. a) Fault structure: Colored lines are hanging wall cut-offs for seismic horizons, color-coded according to their respective ages. The Terningen East fault forms a laterally continuous fault surface at depth while consisting of three overlapping hard-linked segments (F1-F3) in its upper half. b) Strike: The fault strikes N to NNE with dip-oriented corrugations of the fault surface indicating dip-slip kinematics. c) Dip: A steep upper segment detaching in a gently dipping lower segment at ~SU2 level. The upper steep segment is punctuated by a less steep section in the middle, giving a ramp-“flat”-ramp geometry. d) Throw plotted at hangingwall cut-off: Throw values projected onto the Terningen East fault shows several distinct throw maxima separated by throw minima, indicating nucleation in different stratigraphic levels at different times. Flat-topped throw anomalies represent surface-breaching faults and correlate with growth packages observed on seismic data. e) Throw-length (T-X) plots for seismic horizons representing the bases of SU8, SU6 and SU4 growth packages. The bell-shaped profile with several higher-order throw maxima and minima describes the throw behaviour of all three horizons and suggests some initial displacement on many fault segments prior to segment linkage and subsequent displacement accrual on the resulting larger segments. A major segment boundary, seen here as a local throw minima superimposed on the bell-shaped throw profile at approximately 19 km along fault length, remains in the same position after reactivation through dip linkage following burial of the Late Permian fault system. Seismic data courtesy of TGS.

Fig. 12: Transverse folds related to segmentation in the Terningen East fault as imaged in seismic data. a) Transverse folds displayed in “staircase” plot with three base synrift horizons connected by vertical seismic lines oriented along strike. Transverse fold trajectories are produced by tracing syncline and anticline hinges vertically up stratigraphy. Fold amplitudes depend on the differential displacement between fault centers and tips and are attenuated into the hangingwall in a direction perpendicular to their parent faults. Using vertical seismic lines between the base synrift horizons gives variable distances to the examined fault and therefore variable attenuation of transverse folds. b) Seismic amplitudes draped onto a copy of the 3D fault surface shifted approximately 350 m into the hangingwall. Significant local variations in fault dip, such as the ramp-flat-ramp geometry juxtaposed against SU5 in the hangingwall, create some artifacts and the affected part of the figure should be interpreted with care. Most trajectories are focused around growth packages, tipping out up section as transverse growth basins are filled. Note the prominent transverse syncline representing the maximum displacement for Carboniferous rifting (SU2), which extends through the throw maximum for Late Permian rifting (SU4). The adjacent transverse anticline, which may be interpreted as a fault segment boundary, extends from base SU2 to lower SU5, where it abuts the F1-F2 segment boundary. Seismic data courtesy of TGS.

Fig. 13: Links between local throw anomalies and transverse folds. a) Seismic section and T-X plot showing strong correlation between local throw anomalies and transverse folds; throw maxima and minima relate to hangingwall transverse synclines and anticlines, respectively. Seismic section parallel to strike of F2 in the Terningen East fault. b) Throw projection for F2 in the Terningen East fault with hangingwall horizon cutoffs. Curvatures of hangingwall cutoffs and throw contours are attenuated updip from Upper SU5 to SU8. Seismic data courtesy of TGS.

Fig. 14: Isochore thickness maps, seismic sections from F1 and F2 segments of the Terningen East fault and a proposed evolutionary model for three successive stages during Aptian rifting (SU8a) show extensional fold growth impacting accommodation evolution and sedimentary infill. (a) iB-K7: Extensional faulting nucleating above an older buried fault system (Late Permian). Reflectors diverge towards the fault. (b) K7 – ilA: Fold growth shifting the depocenter basinward while truncating strata near the crest of the rising fault-bend anticline. (c) ilA-K8: Fold growth ceases and growth packages become thickest near the faults. Seismic data courtesy of TGS.

5.3. Article 3: From supradetachment to rift basin: continental to marine deposition in the Paleogene Bandar Jissah Basin, NE Oman

Key words: extensional tectonics, supradetachment basins, rift basins, growth packages, tectonics and sedimentation, alluvial fan, carbonate ramp

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The third article in this thesis investigates the interplay between extensional deformation and mixed carbonate-siliciclastic deposition based on outcrop studies in the Paleogene Bandar Jissah Basin, NE Oman (Fig. 15). This article adds to the understanding of accommodation development and mixed sedimentation in extensional basins that change character over time; initially displaying the characteristics of a supradetachment basin before transitioning towards rift-style basin development. Addressing a single extensional basin flanking the Saih Hatat metamorphic core complex, this article has both local implications and implications for the extensional development of NE Oman following ophiolite obduction in the Late Cretaceous.

The Oman Mountains have been extensively studied, primarily on account of the extensively outcropping Semail Ophiolite complex that was obducted onto the Arabian plate in the Late Cretaceous (Cooper et al., 2014; Glennie et al., 1974, 1973; Lippard et al., 1986; Rollinson et al., 2014). Although some attention has been devoted to post-obduction extensional faulting (Fournier et al., 2006; Mann et al., 1990; Nolan et al., 1990; Searle, 2007; Searle et al., 2004), this topic remains under-explored, particularly with respect to detailed studies targeting single extensional basins. Article 3 documents extensional fault-controlled deposition of the upper Paleocene to middle Eocene Jafnayn, Rusayl and Seeb formations in the Bandar Jissah Basin. Located in a continental to shallow marine environment between the Saih Hatat metamorphic core complex and the Arabian neo-Tethys (Fig. 15), the Bandar Jissah Basin fill consists of

both hinterland-derived coarse siliciclastics and locally produced carbonate sediments. Jafnayn Fm alluvial fan conglomerates are deposited onto ophiolitic basement and grade N into conglomeratic braidplain and mouthbar conglomerates, mixed carbonate-siliciclastic shoreface sediments and carbonate ramp wackestones to grainstones dominated by larger foraminifera. “Instant” accommodation increases interpreted to result from slip events in controlling faults lead to rapid transgressions of the alluvial fan deposits, which display a backstepping trend. A late Paleocene age of basin formation is based on occurrences of the calcareous algae *Distichoplax biserialis* in shallow marine mixed carbonate-siliciclastic sandstones deposited between two alluvial fan successions following shoreline transgression. Based on cross-cutting relationships between studied faults, depositional style and comparisons between sedimentary and tectonic transport directions, it is suggested that the Jafnayn and Rusayl formations record deposition in a supradetachment basin that is accommodated by displacement along the Banurama detachment. Sediment transport directions recorded in the Rusayl and Seeb formations reflect drainage diversion caused by growth of a basin-scale monocline linked to movement along this detachment. The syn-sedimentary growth of the monocline is emphasized by Seeb Fm limestone growth packages with prograding nummulitic clinoforms (Fig. 16a).

The third article further documents the transition from a supradetachment basin setting to deposition of the Seeb Fm in a rift-style setting controlled by the Marina and Yiti Beach faults (Fig. 17). Steep rift faults give smaller and lower-relief catchments as compared to the abandoned Banurama detachment. Together with the accommodation surplus typical for the proximal hangingwall in rift basins, the reduced catchment size and relief result in a smaller siliciclastic footprint on hangingwall deposits, particularly outside the most proximal positions, as the basin transitions from a supradetachment basin to a rift-style basin setting. The overall south-to-north accommodation increase recorded for the whole basin fill is modified by the Marina and Yiti Beach faults, with facies distributions mimicking fault strike. Syn-sedimentary faulting in the Qantab Subbasin is documented as growth packages in the immediate Marina fault hangingwall (Fig. 16b). In the Yiti Beach subbasin, syn-sedimentary faulting is suggested by reef buildups on the Yiti Beach fault plane, grading basinwards into foraminiferal wackestones.

Article 3 documents the role of the Wadi Kabir Fault that plays an important role for preservation and erosion of Paleogene strata in its hangingwall. Inferred segmentation of the Wadi Kabir Fault caused transverse folding of hangingwall strata. Ultimately, Paleogene sediments were preserved near transverse synclines and eroded near transverse anticlines.

Fig. 15: a) Overview map showing the NE Arabian Peninsula. Red box gives location of b). b) Main structural elements of the larger study area between Ruwi and Yiti Beach modified from (Le Métour et al., 1992). Stereoplots for the Wadi Kabir and Yiti Beach faults display fault planes and slickensides. Banurama detachment stereoplot shows fault planes with slickensides in addition to stretching lineations measured within the Saih Hatat metamorphic core complex in the footwall of the Banurama detachment. Stereoplot for the Qantab subbasin monocline displays contoured poles to bedding planes. Satellite photo courtesy of Bing/Microsoft.

Fig. 16: Seeb Fm carbonate growth sections in the Qantab subbasin. a) Lower Seeb Fm growth package in Qantab subbasin monocline with supporting logs and proposed model. b) Upper Seeb Fm growth packages as seen along strike in the immediate hangingwall of the Marina fault. Strata expand towards inferred local displacement maximum. Field of view for photographs indicated in map.

Fig. 17: Evolutionary model of the Bandar Jissah Basin during deposition of the Seeb Fm (pre-Wadi Kabir Fault). Accommodation was first controlled by the Banurama detachment and later modified by the Marina and Yiti Beach faults.

6. Discussion, applications and concluding remarks

Extensional basins are important because they hold economic potential (hydrocarbon exploration) and can have environmental (CO₂ storage prospecting) and societal impacts (groundwater exploration, geohazard evaluation). Exploiting these potentials, however, is difficult because of the variability of extensional fault and fold properties, accommodation development, sediment facies distribution, and climatic and tectonic setting from one basin to the next, challenging design of generic models. This project builds on previous work on such topics as structural evolution of extensional basins (e.g. Gibbs, 1984; Rotevatn and Jackson, 2014; Worthington and Walsh, 2016), tectonostratigraphy of rift basins (e.g. Gawthorpe and Leeder, 2000; Henstra *et al.*, 2017; Gawthorpe *et al.*, 2018) and supradetachment basin development (e.g. Friedmann and Burbank, 1995; Oner and Dilek, 2011; Osmundsen and Péron-Pinvidic, 2018). The project advance current concepts and provide novel ideas that are applicable to extensional basins under a variety of conditions. This section serves to synthesize the implications of the current project on the understanding of extensional basins; particularly the role extensional folding has on accommodation evolution and architecture of syn-deformational strata.

Articles 1 and 2 highlight the links between evolution of the Fingerdjupet Subbasin in the SW Barents Sea and reactivations in the N to NNE striking, E-dipping Terningen Fault Complex, which separates the Fingerdjupet Subbasin from the Ringsel Ridge to the west. A Late Triassic to Early Cretaceous high-resolution seismic and tectonostratigraphic framework for the Fingerdjupet Subbasin is presented in **Article 1**, with implications for the Barents Shelf and circum-Arctic areas. The growth of basin-bounding faults from the Carboniferous to Early Cretaceous, including relations to inherited tectonic fabrics, is discussed in **Articles 1 and 2**. The Fingerdjupet Subbasin occupies a position between the deep Bjørnøya Basin in the west and the deeply eroded Bjarmeland Platform in the east. Results from **Articles 1 and 2** can be projected into these neighboring areas, where detailed analysis of tectonic evolution is inhibited by large burial depth and limited seismic resolution (Bjørnøya Basin) or lack of preserved strata (Bjarmeland Platform). Carboniferous, Late Permian, latest Jurassic to Hauterivian, and Aptian activity is indicated for the N-S/NNE-SSW striking Terningen Fault Complex and associated faults. Other prominent fault populations discussed in **Article 1** strike E-W and NW-SE. The latter population is not time-constrained, but the former is connected with growth packages of latest Triassic to Middle Jurassic age. This timing of displacement on E-W faults compares favorably with field observations on the northern Barents Shelf (Anell *et al.*, 2013; Osmundsen *et al.*, 2014) and seismic studies in the Hammerfest Basin (Mulrooney, Leutscher and Braathen, 2017), establishing this hitherto poorly understood extensional faulting event as regionally significant. **Article 1** elevates the understanding of several other important events that affected the Barents Shelf from the Devonian to Early Cretaceous, notably by (i) linking a deep, gently dipping tectonic fabric critical for Fingerdjupet Subbasin evolution to outcrop studies on Bjørnøya (~50 km NW), where post-Caledonian extensional faults exploited Caledonian contractional

fabrics (Braathen *et al.*, 1999), and (ii) describing a NW-prograding deltaic system as related to Early Barremian uplift and erosion of the Loppa High, supporting the conclusions of Indrevær *et al.* (2017).

Article 2 assesses the multi-stage rift aspect of the Fingerdjupet Subbasin and demonstrates the complex interplay between fault growth characteristics, mode of fault reactivation, fault shape and hangingwall deformation with implications for accommodation and depositional architecture. **Article 2** utilizes depositional architecture to deduce the timing of extensional faulting, fault linkage and folding. Growth-basin style relates to syn-sedimentary fault properties. Lateral offsets between initially decoupled deep and shallow fault segments result in ramp-flat-ramp fault geometries upon dip linkage. Displacement in ramp-flat-ramp faults initiate fault-bend anticlines that experience subaerial exposure of anticline crests, causing intra-formational truncation of strata in anticline crests. Folding limits accommodation near the controlling fault and sediments accumulate in depocenters further into the hangingwall. Transverse folds that result from lateral fault segmentation controls accommodation along strike of the fault array. **Article 2** presents transverse fold trajectory analysis, a novel technique for transverse fold visualization and analysis that aids in highlighting favorable conditions for accumulation of reservoir-quality sediments and trapping structures in the hangingwall of large normal faults. This represents fundamental knowledge about fault and fold growth, depocenter evolution and syn-deformational sedimentation also applicable to other extensional basins. Utilizing transverse fold trajectory analysis, **Article 2** documents the remarkable perseverance of transverse folds during several phases of vertically decoupled faulting, highlighting the importance of structural inheritance in multi-stage rifts.

Article 3 documents the tectonostratigraphy of the Bandar Jissah Basin, northeastern Oman as it developed on the flank of the Saih Hatat metamorphic core complex that followed orogenic collapse in the Oman Mountains during the Late Cretaceous and onwards (e.g. Braathen and Osmundsen, submitted; Jolivet *et al.*, 1998; Warren and Miller, 2007). Fossil evidence presented in **Article 3**, suggests that the Bandar Jissah Basin started accumulating sediments in the late Paleocene. The basin occupied a low-latitude marginal marine position between the Saih Hatat metamorphic core complex and the Tethys Sea. High-relief catchment areas and ephemeral runoff resulted in deposition of coarse siliciclastic sediments onto a carbonate ramp without any apparent limiting effects on carbonate production. **Article 3** concludes that the Bandar Jissah Basin initiated as a supradetachment basin with normal displacement on the Banurama detachment during deposition of the Jafnayn Fm, wherein backstepping alluvial fans give way to carbonate ramp deposits, reflecting increasing distality towards ~N. The dominant E-directed transport of sediments in the Rusayl and lower Seeb formations in the Qantab Subbasin attests to growth of the Qantab subbasin monocline, which is linked with rollover folding initiated by movement on the Banurama detachment. Lower Seeb Fm growth strata with E prograding nummulitic limestone foresets are documented in the monocline, emphasizing its syn-sedimentary relevance. The Marina and Yiti Beach faults became active during deposition of the upper Seeb Fm, splitting the Bandar Jissah Basin into the Qantab and Yiti Beach subbasins, separated by the Marina fault. The upper Seeb Fm display

characteristics typical for rift-basin fill; facies belts organized along strike with major structures and syn-tectonic growth packages in the immediate hangingwall that display along-strike thickness variations relating to displacement variations, similar to observations of transverse growth basins in **Article 2**. Near-fault growth packages reflect subsidence/uplift rates atypical of supradetachment basins, where large-magnitude footwall rebound following detachment faulting limits accommodation near the faults and sediments accumulate in distal depocenters. **Article 3** emphasize how modifications to the overall N-directed accommodation increase caused by displacement on the SW-NE striking Marina fault and W-E striking Yiti beach fault complicated stacking patterns by setting up multiple proximal-distal axes within the same basin system, and serves as a reminder for the three-dimensional nature of accommodation. **Article 3** suggests the prominent Wadi Kabir Fault is late with respect to the basin fill, but has affected preservation of strata through fault-displacement folding in its hangingwall; remnants of a much larger Paleogene basin are preserved in hangingwall transverse synclines while ophiolitic rocks, which represent the substrate in the Bandar Jissah Basin, outcrop in transverse anticlines.

Some of this PhD project's strength lies in the differences between the studied basins. Differences in terms of (i) duration of active basin formation; (ii) paleogeographic setting and (iii) basin fill lithology questions the validity of the Bandar Jissah Basin as a direct analogue to the Fingerdjupet Subbasin. This project provides, however, the opportunity not only to evaluate one particular type of extensional basins, but to make considerations that apply to extensional basins in general, regardless of their respective age, fault properties and geological setting. The transition between supradetachment basin and rift basin characteristics in structural style and accommodation development can be documented in the Bandar Jissah Basin (**Article 3**) and inferred in the Fingerdjupet Subbasin (**Articles 1 & 2**); investigations from both areas advocate that the interaction between steep rift faults and low-angle detachments cause diagnostic signatures in hangingwall deformation style and sedimentary architecture, albeit at different spatial and temporal scales. Rollover folding in a relatively small area associates with growth packages deposited during a single extensional phase in the Bandar Jissah Basin. Semi-regional rollover folding fundamentally controlled accommodation and deposition during at least four phases of rifting between the Carboniferous and Early Cretaceous in the Fingerdjupet Subbasin. Transverse folds that result from differential displacement along the length of a fault array are important features recognized in both studied basins. **Articles 1, 2 & 3** document their syn-tectonic significance for accommodation and sedimentary growth package architecture. Post-depositional transverse folding is important for trap formation (**Articles 1 & 2**) and preservation of strata (**Article 3**). **Article 2** defines different styles of growth package architectures that reflect different characteristics of accommodation-controlling extensional faults and folds. These definitions also apply to the Bandar Jissah Basin; **Article 3** documents that growth strata in the Seeb Fm accumulated in rollover basins (lower Seeb Fm) in addition to "standard" growth basins, where lateral thickness variations in growth packages was constrained by transverse folds (upper Seeb Fm).

This thesis brings forth updated insights into the Fingerdjupet Subbasin and Bandar Jissah Basin and into the relationship between extensional fault and fold growth, accommodation development and sedimentary architecture in general. The significance of extensional folding of different extent, magnitude and time scales is supported by observations and interpretations of datasets that differ in terms of resolution, tectono-climatic setting and duration of faulting. The insights provided in this thesis are applicable elsewhere and represent a step towards a general understanding of extensional basins.

Further work

While the current project advances concepts of extensional basin evolution, many questions remain unanswered and several new questions have been raised as this work progressed. Generally, the response of different sedimentary systems on different styles of extensional faulting and folding must be assessed in more basins before this knowledge can be utilized predictively in extensional basin settings, for instance where seismic imaging is poor or outcrops are few and far between. The seismic dataset used for this work is of excellent quality and holds a great potential for further studies on several scales, from providing insights into circum-Arctic geological evolution to targeting specific stratigraphic intervals or faults. The Fingerdjupet Subbasin has three dominant fault populations (N-S/NNE-SSW, E-W, NW-SE) that must reflect changing stress regimes. Unanswered questions remain for all three trends: (1) N-S/NNE-SSW faults have been instrumental for Fingerdjupet Subbasin evolution and inferred to exploit a fabric inherited from the Caledonian Orogeny. The direct link, however, is unclear. Analysis of pre-Carboniferous strata involving interpretations of intra-basement seismic fabrics linked with onshore observations might help clarify the deep history of the basin. **Article 3** outcrop studies provide details of supradetachment basin fill that can complement such investigations. (2) The E-W fault population has been addressed in **Article 1** and Late Triassic to Jurassic faulting has been discussed by others (Anell *et al.*, 2013; Osmundsen *et al.*, 2014; Collanega *et al.*, 2017; Mulrooney, Leutscher and Braathen, 2017). The cause of this extension and the regional implications remain unclear as the E-W striking faults were active between two phases of activity in N-S/NNE-SSW fault populations, thus indicating competing stress regimes (**Article 1**). Moreover, the small displacement/length-ratios displayed by the E-W faults are enigmatic, encouraging detailed kinematic analyses to further understand their importance. (3) The small offsets, lack of detectable growth packages and limited preserved stratigraphy in the Fingerdjupet Subbasin makes the NW-SE trend enigmatic both in terms of timing and cause, necessitating further studies that involve high-resolution data and/or study areas where younger stratigraphy is preserved.

Although this work has documented remarkably persistent transverse folds in the Fingerdjupet Subbasin, such folds may not be typical features of all multi-stage extensional basins. The temporal perseverance of transverse folds can be tested in other basins by utilizing the techniques for visualization and transverse fold trajectory analysis presented in this work. Some uncertainties to the transverse fold trajectory analysis is introduced when preparing the seismic sections used for analysis; seismic interpretation software used for this work only provides the opportunity for *vertical* shifting of seismic surfaces.

Therefore, fault shape must be taken into consideration in transverse fold trajectory analysis as outlined in **Article 2**; the seismic section that display transverse folds in the hangingwall has the shape of the fault surface, and vertical shifts of the seismic section will give variable distances to the fault if the fault is non-planar. New methods that support fault-perpendicular shifts of any given point on the fault surface would reduce uncertainty in the current method. Furthermore, the concepts here are based exclusively on seismic data and would benefit from ground-truthing in relevant field locations.

The onshore part of the Bandar Jissah Basin is small and the cross-cutting relationships between the different faults are inferred in **Article 3**, but not always well constrained on account of limited outcrops. Analysis of seismic data from the offshore part of the basin can promote a larger understanding of the relationships between faults and folds that affected accommodation and sediment distribution in the Paleogene. Moreover, the regional understanding of post-orogenic extensional faulting would benefit from comparative studies of other basins flanking the Saih Hatat and Jebel Akdar metamorphic core complexes.

7. References

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8. Articles

8.1. Article 1 – Jurassic to Early Cretaceous basin configuration(s) in the Fingerdjupet Subbasin, SW Barents Sea

Serck, C. S.¹, Faleide, J. I.^{1,2}, Braathen, A.¹, Kjølhamar, B.³, & Escalona, A.⁴ (2017). Jurassic to early cretaceous basin configuration (s) in the Fingerdjupet Subbasin, SW Barents Sea. *Marine and Petroleum Geology*, 86, 874-891. DOI: <https://doi.org/10.1016/j.marpetgeo.2017.06.044>

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Research paper

Jurassic to Early Cretaceous basin configuration(s) in the Fingerdjupet Subbasin, SW Barents Sea

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ABSTRACT

The Fingerdjupet Subbasin in the southwestern Barents Sea sits in a key tectonic location between deep rifts in the west and more stable platform areas in the east. Its evolution is characterized by extensional reactivation of N-S and NNE-SSW faults with an older history of Late Permian and likely Carboniferous activity superimposed on Caledonian fabrics. Reactivations in the listric NNE-SSW Terningen Fault Complex accommodated a semi-regional rollover structure where the Fingerdjupet Subbasin developed in the hangingwall. In parallel, the Randi Fault Set developed from outer-arc extension and collapse of the rollover anticline.

N-S to NNE-SSW faults and the presence of other fault trends indicate changes in the stress regime relating to tectonic activity in the North Atlantic and Arctic regions. A latest Triassic to Middle Jurassic extensional faulting event with E-W striking faults is linked to activity in the Hammerfest Basin. Cessation of extensional tectonics before the Late Jurassic in the Fingerdjupet Subbasin, however, suggests rifting became localized to the Hammerfest Basin. The Late Jurassic was a period of tectonic quiescence in the Fingerdjupet Subbasin before latest Jurassic to Hauterivian extensional faulting, which reactivated N-S and NNE-SSW faults. Barremian SE-prograding clinoforms filled the relief generated during this event before reaching the Bjarmeland Platform. High-angle NW-prograding clinoforms on the western Bjarmeland Platform are linked to Early Barremian uplift of the Loppa High. The Terningen Fault Complex and Randi Fault Set were again reactivated in the Aptian along with other major fault complexes in the SW Barents Sea, leading to subaerial exposure of local highs. This activity ceased by early Albian. Post-upper Albian strata were removed by late Cenozoic uplift and erosion, but later tectonic activity has both reactivated E-W and N-S/NNE-SSW faults and also established a NW-SE trend.

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1. Introduction

The Fingerdjupet Subbasin of the southwestern Barents Sea has thick Jurassic to Lower Cretaceous deposits buried relatively shallow in the present day subsurface (Figs. 1 and 2). This contrasts both the Bjarmeland Platform to the east, where late Cenozoic uplift and erosion has removed much of the Lower Cretaceous section, and the Bjørnøya Basin to the west, where present burial depth makes high-resolution seismic imaging of these deposits

challenging. The Fingerdjupet Subbasin therefore has a cornerstone position in this part of the southwestern Barents Sea, and may provide valuable insights into the Jurassic to Early Cretaceous evolution of not only the study area, but of the whole region.

Previous workers have described extensional faulting in the Fingerdjupet Subbasin (e.g. Rønnevik and Jacobsen, 1984; Gabrielsen et al., 1990; Faleide et al., 1993a, 1993b; Gudlaugsson et al., 1998), but data coverage and resolution has not allowed for a detailed analysis of the timing of extensional faulting events. For this study we utilize a large, high-resolution 3D dataset together with information from nearby hydrocarbon exploration wells (7321/7-1, 7321/8-1 and 7321/9-1; Fig. 3) and a shallow stratigraphic borehole (7320/3-U-1). The 3D dataset allows for semi-

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Fig. 1. Map showing study area in the southwestern Barents Sea with structural elements, exploration wells, shallow coreholes and location of presented seismic profiles. (a) Arctic overview map, SW Barents Sea indicated in red box. Abbreviations: HFZ: Hornsund Fault Zone, SFZ: Senja Fracture Zone. Modified from Jakobsson et al. (2012). (b) SW Barents Sea basins and highs. Green outline indicate 3D seismic cube used for this study, stippled red line indicates location of Fig. 2 and red box indicate study area. Basin colours indicate main periods of basin formation according to Faleide et al. (2015): Red corresponds to Late Paleozoic, blue corresponds to Late Jurassic – Early Cretaceous and yellow corresponds to Late Cretaceous – Paleocene. Abbreviations: BB: Bjørnøya Basin, BjFC: Bjørnøyrenna Fault Complex, FSB: Fingerdjupet Subbasin, HfB: Hammerfest Basin, HFC: Hoop Fault Complex, HFZ: Hornsund Fault Zone, LH: Loppa High, MB: Maud Basin, MH: Mercurius High, NB: Nordkapp Basin, NH: Norsel High, OB: Ottar Basin, PSP: Polhem Subplatform, RLFC: Ringvassøy-Loppa Fault Complex, SFZ: Senja Fracture Zone, SR: Senja Ridge, SH: Stappen High, SB: Sørvestnaget Basin, TFFC: Troms-Finnmark Fault Complex, TB: Tromsø Basin, VH: Veslemøy High, VVP: Vestbakken Volcanic Province. Map modified from (Faleide et al., 2015). (c) Berriasian-Tithonian time structure map showing the main structural elements in the study area. Three structural elements have been defined in this work: The Ringsel Ridge, Terningen Fault Complex and Randi Fault Set. Some important faults are indicated in dark grey. Green outline indicates extent of 3D seismic data used for this study. Black stippled lines define locations of shown seismic sections. Seismic data courtesy of TGS.

regional horizon and fault mapping and can be considered the outline of the study area (Fig. 1). Timing of extensional faulting episodes displayed by sedimentary growth packages is examined in local depocenters, where seismic and stratigraphic resolution is at the highest possible level.

We recognize the seismic dataset holds great potential for investigation of sedimentary deposits and associated fault systems from pre-Carboniferous to recent, and some considerations around

basin history prior to the latest Triassic have been made. The aim of the current study, however, is to establish a detailed seismic- and tectonostratigraphic framework for the Jurassic to Lower Cretaceous deposits of the Fingerdjupet Subbasin.

2. Geological framework

The present day Barents shelf is located at the northwestern

corner of the Eurasian plate (Fig. 1a) (Faleide et al., 2008). The geological evolution of the area is characterized by a series of compressional and later extensional events related to continent assembly and breakup, respectively (e.g. Faleide et al., 1993b, 1996; Gudlaugsson et al., 1998). The southwestern Barents Sea consists of a complex pattern of basins and highs which strikes predominantly NE-SW and N-S (Fig. 1b) (Faleide et al., 1993b; Gudlaugsson et al., 1998). The Fingerdjupet Subbasin (Fig. 1c) was defined as the shallow, northeastern part of the Bjørnøya Basin by Gabrielsen et al. (1990).

2.1. Post-Caledonian extensional faulting

The study area has been affected by at least five post-Caledonian phases of extensional faulting: Late Devonian orogenic collapse, mid-late Carboniferous extensional faulting, Late Permian to Early Triassic extensional faulting focused in the west, Middle Jurassic–Early Cretaceous extensional faulting and Late Cretaceous–Cenozoic rifting (Gudlaugsson et al., 1998; Faleide et al., 1993b, 2015; Glørstad-Clark, 2011). While the post-Caledonian evolution of the SW Barents Sea has been dominated by these extensional events, some inversion of major fault complexes have also previously been described (e.g. Faleide et al., 2008; Gabrielsen et al., 1997; Indrevær et al., 2016).

The study area is most likely underlain by Caledonian basement (Gernigon and Brønner, 2012; Ritzmann and Faleide, 2007) that was assembled by thrusting during the Caledonian Orogeny when Laurentia and Baltica collided in the Silurian to Early Devonian (Doré, 1991). A Caledonian terrain affected by collapse has been inferred both in the SW Barents Sea, mainly based on magnetic data (Gernigon and Brønner, 2012), and further north between Bjørnøya and Svalbard (Breivik et al., 2003; Gudlaugsson and Faleide, 1994; Ritzmann and Faleide, 2007). N to NNW trends seen in magnetic data in the area between Svalbard and the Loppa High are believed to represent the structural grain of Caledonian thrusting (Barrère et al., 2009; Gernigon et al., 2014; Gernigon and Brønner, 2012). On Bjørnøya, Braathen et al. (1999b) provided evidence for WNW-directed Caledonian thrusting and Carboniferous extensional reactivation of these contractional structures, and Worsley et al. (2001) subsequently documented Carboniferous syntectonic deposits along mainly N-S striking normal faults. Gernigon et al. (2014) described a major NW-dipping detachment along the northern flank of the Stappen High and SW-to-W-dipping detachments in the Bjørnøya Basin, while Gudlaugsson et al. (1998) described an E-dipping detachment in the Fingerdjupet Subbasin (Fig. 2). To explain this complexity, Gernigon et al. (2014) suggested an accommodation or relay zone between major detachments exist between the Loppa and Stappen highs.

In mid-Carboniferous to Late Carboniferous times, a 300 km wide and at least 600 km long zone of rifting developed in the Barents Sea, resulting in a series of extensional basins separated by fault-bounded highs, e.g. the Nordkapp, Maud, Bjørnøya, Ottar and Tromsø basins (Faleide et al., 2015; Gudlaugsson et al., 1998) (Fig. 1b). The Carboniferous rift structures, mainly with a clastic basin fill but also some evaporites, are capped by a regional carbonate platform that developed during latest Carboniferous–early Permian times (e.g. Faleide et al., 2015; Henriksen et al., 2011b; Larssen et al., 2002). It has been suggested that the Bjørnøya Basin and Fingerdjupet Subbasin formed as rift basins initiated in mid-Carboniferous times (Dengo and Røssland, 1992; Gudlaugsson et al., 1998). For the Bjørnøya Basin, this suggestion is supported by the presence of salt diapirs as indicated by Breivik et al. (1998) and better constrained in recently acquired seismic and potential field data. Investigations from the northern Bjørnøya Basin and southern Stappen High by Blaich et al. (2017) also indicate mid-

Carboniferous rifting with deposition of growth packages along NE-SW striking faults.

The western parts of the Barents Sea experienced another phase of extension in the Late Permian to Early Triassic (Gudlaugsson et al., 1998). Recently, improved seismic imaging has allowed interpretation of growth packages of this age in the Bjørnøya Basin, Fingerdjupet Subbasin and southern Stappen High (Blaich et al., 2017; Faleide et al., 2015; Glørstad-Clark, 2011; Kamp, 2016). A distinct growth sequence in the Bjørnøya Basin along the Leirdjupet Fault Complex can be tied to a similar unit in the Fingerdjupet Subbasin, where age control is provided by well 7321/8-1 (“Norwegian Petroleum Directorate Factpages,” 2017).

The underfilled epicontinental basin that existed in the Barents Sea area in the Early Triassic was gradually infilled by W-NW prograding clastic wedges from earliest–Middle Triassic (Glørstad-Clark et al., 2010). The Fingerdjupet Subbasin persisted as an underfilled depocenter throughout the Early–Middle Triassic but was filled by fluvio-deltaic deposits in the Late Triassic (Glørstad-Clark et al., 2010; Kamp, 2016). Kamp (2016) described growth packages within Upper Triassic strata linked to N to NNE striking faults in the Fingerdjupet Subbasin, thus suggesting a Late Triassic extensional faulting event. Osmundsen et al. (2014) described fault-controlled sedimentary architecture relating to E-W to NW-SE striking normal faults in the Tschermakfjellet and De Geerdalen formations on Edgeøya (Carnian and Carnian to early Norian, respectively) and Flatsalen Formation (Norian) on Hopen (Fig. 1). Mulrooney et al. (2017) suggested Mesozoic extensional faulting along crudely E-W striking faults in the Goliat area of the Hammerfest Basin started in the Norian.

The Middle to Late Jurassic was a period of regional extension, resulting in a regional rift basin extending from the Rockall Trough west of Ireland to the Barents Sea (Faleide et al., 1993b). The structuring of the southwestern Barents Sea from the late Middle Jurassic to earliest Cretaceous was closely affiliated with both the North Atlantic and Arctic regions, represented by the rifting in the North Atlantic and Amerasia basins, respectively (Faleide et al., 1993b). Mesozoic rifting in the Hammerfest Basin culminated with a Late Jurassic to earliest Cretaceous rift event which also affected the Bjørnøya Basin and southern Stappen High, reactivating the pre-existing tectonic grain (Blaich et al., 2017; Faleide et al., 1993b). Extensional faulting on E-W striking faults in the Hammerfest Basin had ceased by early Barremian times, when the Loppa High was uplifted, causing inversion in normal fault complexes along its flanks (Indrevær et al., 2013).

Faleide et al. (1993a) attributed the N-S to NNE-SSW horst and graben pattern of the Fingerdjupet Subbasin to Late Jurassic rifting with later local reactivation. North Atlantic tectonism appears to dominate increasingly through the Early Cretaceous, and major extension along the western Barents Sea margin led to the formation and/or rejuvenation of several fault complexes such as the Troms-Finnmark Fault Complex, Ringvassøy-Loppa Fault Complex, Bjørnøyrenna Fault Complex and Leirdjupet Fault Complex, and rapid subsidence of the adjacent Harstad, Tromsø and Bjørnøya basins (Faleide et al., 1993b). The Leirdjupet Fault Complex, which separates the deep Bjørnøya Basin from the shallower Fingerdjupet Subbasin, was active at this time, and both erosional truncation of intra-basinal highs and growth packages banked onto the fault have previously been described (Faleide et al., 1993b). Faleide et al. (1993b) recognized Berriasian/Valanginian and Hauterivian/Barremian phases of extension in the western Hammerfest Basin but were unable to resolve them on seismic data. Although an extensional regime prevailed in the SW Barents for the better part of the Early Cretaceous, early Barremian uplift of the Loppa High caused inversion in the surrounding fault complexes and led to subaerial exposure of the Loppa High (Indrevær et al., 2016).

Fig. 2. Composite seismic profile showing the main structural elements of the study area and adjacent region. Major structures are; from E to W: Hoop Fault Complex, Bjarmeland Platform, Randi Fault Set (Appendix), Fingerdjupet Subbasin, Temingen Fault Complex (Appendix), Ringesel Ridge (Appendix), Leirdjupet Fault Complex and Bjørnøya Basin. Dotted lines indicate changes in seismic line direction and boundaries between different seismic datasets. Profile location is given in Fig. 1b. Seismic data courtesy of TGS.

Fig. 3. Correlation of lithostratigraphic groups from wells 7321/7-1, 7321/8-1 and 7321/9-1 in the Fingerdjupet Subbasin. Stippled outline indicates stratigraphy in focus for the present work. Gamma ray logs and well information from “Norwegian Petroleum Directorate Factpages” (2017).

Magmatism within the High Arctic Large Igneous Province (HALIP, ~125 Ma), likely related to the rifting, breakup and early stage of seafloor spreading in the Amerasia Basin, is suggested to have caused regional uplift of the northern Barents margin and adjacent areas of the proto-Arctic (e.g. Senger et al., 2014). In the Barremian and Aptian, large volumes of sediments were shed from the uplifted region, allowing large fluvio-deltaic complexes to prograde southeastwards past Svalbard to the southwestern Barents Sea area (Faleide et al., 1993b, 2015; Midtkandal and Nystuen, 2009; Marín et al., 2016). Lower Cretaceous intrusive and extrusive igneous rocks are found throughout the Barents Sea (Polteau et al., 2016), but so far not documented in the southwestern Barents Sea. The igneous activity has been dated to 122–124 Ma based on samples from Svalbard and Franz Josef Land (Corfu et al., 2013). Based on field-, seismic- and potential field data, magmatism on the Barents shelf E and SE of Svalbard display a NNE trend (Grogan et al., 2000; Minakov et al., 2012).

Mesozoic extension along the western Barents Sea margin affecting the Bjørnøya, Harstad and Tromsø basins peaked in the Aptian (Faleide et al., 1993b). This is supported by improved seismic imaging and interpretation of the northern Bjørnøya Basin and southern Stappen High (Blaich et al., 2017). The Bjørnøya Basin,

which was faulted along NNE-SSW and N-S faults, experienced rapid subsidence and infill also after the cessation of faulting (Faleide et al., 1993a, 1993b). The Hammerfest Basin not only experienced extension in faults along the E-W basin axis, but also saw an increased influence of North Atlantic tectonic activity as evident by normal faulting in the N-S trending Ringvassøy-Loppa Fault Complex (Faleide et al., 1993b).

In the Late Cretaceous and Paleogene the Barents Sea area was affected by another phase of extension which culminated with breakup and seafloor spreading in the Norwegian-Greenland Sea in the earliest Eocene (Faleide et al., 2008). Narrow basins in the SW Barents Sea (e.g. Sørvestsnaget Basin) (Faleide et al., 2008) and NE Greenland (Wandel Sea Basin) (Svennevig et al., 2017) developed within the so-called De Geer Zone in response to regional shear. The Cenozoic western Barents Sea continental margin is characterized by transform faulting in the south, represented by the Senja Fracture Zone, and a rifted segment located southwest of Bjørnøya where extensive volcanism has occurred in the Vestbakken Volcanic Province (Faleide et al., 2008). Further north, there is an initially sheared and later rifted margin along the Hornsund Fault Zone (Faleide et al., 2008). Some fault complexes in the western Barents Sea experienced periods of inversion in the Late Cretaceous

and Paleogene, likely relating to transpression along sheared margin segments (e.g. Faleide et al., 2015, 2008; Braathen et al., 1999a; Gabrielsen et al., 1997; Indrevær et al., 2016; Vågnes et al., 1998).

2.2. Late Cenozoic uplift and erosion

The entire Barents Shelf was uplifted and eroded during the Neogene (Baig et al., 2016; Henriksen et al., 2011a). A significant part of the erosion, and deposition of large volumes of Plio-Pleistocene glacial sediments along the continental margins in the west and north (Dimakis et al., 1998; Faleide et al., 1996; Laberg et al., 2012), was related to the northern hemisphere glaciations, but uplift of large areas was initiated earlier (Oligocene?–Miocene) due to other tectonic causes (Dimakis et al., 1998). Post-Early Cretaceous strata were removed from the Fingerdjupet Subbasin (Faleide et al., 1996; Henriksen et al., 2011a,b). The uplift and associated erosion was greater north of the Fingerdjupet Subbasin, making correlation of the Cretaceous sedimentary succession between Svalbard and the southwestern Barents Sea challenging. The net erosion in the Fingerdjupet Subbasin varies from approximately 1600 m in the south to 2600 m in the north (Henriksen et al., 2011a,b; Baig et al., 2016). The boundary between pre-glacial rocks and Quaternary glacial deposits is marked by the upper regional unconformity (URU) (Solheim and Kristoffersen, 1984).

3. Datasets and methods

Key to this study is an 8600 km² 3D seismic survey which was acquired by TGS in 2013 utilizing ten 6000 m long seismic streamers with a streamer separation of 75 m and an E-W acquisition direction. 3D seismic bin size is 18.75 m × 6.25 m and the dataset extends to 7000 ms TWT. The data is zero-phased with SEG (Society of Exploration Geophysicists) positive standard polarity, where positive amplitudes correspond to an increase in acoustic impedance across an interface. In addition, regional 2D seismic lines acquired by TGS and Fugro between 2006 and 2012 have been used to examine the Fingerdjupet Subbasin in a regional context.

The geometrical characteristics of the seismic packages have been examined through a combination of horizon- and fault mapping (e.g. Figs. 1 and 2). In total 16 horizons have been mapped to investigate the basin architecture. In addition to conventional fault mapping on seismic sections, seismic variance attribute has been draped on the interpreted seismic horizons to illustrate how different parts of the sedimentary succession have been affected by different fault systems. Time-thickness maps produced from the interpreted horizons have been used to highlight and assess variations related to sedimentary systems and/or geometry of sedimentary sinks. Three hydrocarbon exploration wells have been drilled in the Fingerdjupet Subbasin but south of the 3D seismic dataset used for this study, penetrating Lower Cretaceous to Upper Permian stratigraphy. Checkshot data from wells 7321/7-1, 7321/8-1 and 7321/9-1 (Fig. 1), located between 7.5 km and 25 km south of the 3D seismic dataset, give average seismic velocities between ca. 2800 and 4100 m/s for the Lower Cretaceous to Upper Triassic stratigraphy of the Fingerdjupet Subbasin (Table 1). These calculations are used to convert fault throw and thickness of seismic packages from milliseconds Two Way Time [ms TWT] to metres [m]. The maximum frequency of the dominant bandwidth varies with depth, and estimates for seismic resolution for the Upper Triassic, Jurassic and Cretaceous strata are given in Table 2.

In addition, 10 of the 16 interpreted horizons have been correlated with publicly available biostratigraphic and petrophysical data from well 7321/7-1 (Robertson Group, 1989) (Fig. 4). This has allowed for establishing a seismic stratigraphic and

tectonostratigraphic framework for the study area (Fig. 5). Time-thickness maps and corresponding seismic profiles for the sequences are given in Fig. 6. The horizon names reflect the ages of the horizons as inferred from the biostratigraphy report (Robertson Group, 1989). Not all the ages inferred from the biostratigraphy report are based on direct biostratigraphic evidence taken from sidewall cores. Some ages are based on petrophysical log analysis from the well coupled with regional well information, often aided by biostratigraphic evidence above and below. Gamma ray logs as sand/clay indicators are used to gain a brief overview of the depositional setting of lithological groups in the Fingerdjupet Subbasin (Fig. 3), and to support age determination where biostratigraphic evidence is scarce (Fig. 4) (Robertson Group, 1989).

In the 1980's and 1990's, IKU (Continental Shelf Institute, now SINTEF Petroleum Research) drilled a number of shallow stratigraphic boreholes near the main study area. Of particular interest is borehole 7320/3-U-1, which is located within the limits of the 3D seismic survey used for this study (Fig. 1). This 36,2 m core contains Barremian to Tithonian strata with a 3 m thick condensed section of Valanginian age, and thus may provide a data point that can be tied to the available 3D seismic coverage (Århus and Kelly, 1990). Due to constraints in seismic resolution, however, a direct tie remains challenging.

Three new structural elements have been defined (Appendix) and approved by the Norwegian Committee on Stratigraphy (NSK); these are the Ringsel Ridge, Terningen Fault Complex and Randi Fault Set.

4. Fault systems of the Fingerdjupet Subbasin

Fault systems observed in the study area affect different stratigraphic intervals and vary significantly in terms of orientation, geometry and displacement. The main fault trends are NNE-SSW, N-S, E-W and NW-SE. NNE-SSW and N-S faults commonly have a strong affiliation with wedge-shaped seismic packages in the hangingwall and are seen as boundary faults to the Bjørnøya Basin and Fingerdjupet Subbasin (Figs. 1, 2, 6–8). Most faults shown in Fig. 2 have this trend and some are considered significant enough to be given names. These are the Terningen Fault Complex, which defines the western boundary of the Fingerdjupet Subbasin, and the Randi Fault Set, which is seen as densely spaced faults straddling the transition between the Fingerdjupet Subbasin and the Bjarmeland Platform. In the Randi Fault Set, the Bjarmeland Platform rolls over from sub-horizontal to westwards dipping reflectors into the Terningen Fault Complex (Fig. 2). Together, the Leirdjupet and Terningen fault complexes define the Ringsel Ridge.

4.1. NNE-SSW faults

A prominent system of normal faults striking approximately NNE-SSW dominates the study area (Fig. 1). The Ringsel Ridge separates the Bjørnøya Basin from the Fingerdjupet Subbasin and is bounded to the west by the Leirdjupet Fault Complex and to the east by large, east-facing NNE-SSW and N-S oriented normal faults in the Terningen Fault Complex (Figs. 1, 2, 7 and 8). NNE-SSW oriented faults are also observed in the Bjørnøya Basin to the west and in the Hoop Fault Complex and Maud Basin to the east. Faults are planar for the Mesozoic level but some, for instance faults in the Terningen Fault Complex, have a listric expression at depth, where the interpreted fault surface curves into a lower-angle surface at approximately 5 s TWT (Fig. 2, stippled line).

The easternmost fault in the Terningen Fault Complex forms the boundary between the main Lower Cretaceous Fingerdjupet depocenter and the Ringsel Ridge. This fault consists of two main segments where the southern segment is oriented N-S and the

Table 1
Average seismic velocities.

Interval	MD top [m]	MD base [m]	TWT top [s]	TWT base [s]	Δ MD [m]	Δ TWT [s]	Average velocity, $v=2 \times \Delta MD/\Delta TWT$ [m/s]
Lower Cretaceous							
7321/7-1	952	1937	1.03	1.654	985	0.624	3157
7321/8-1	600	1387.5	0.752	1.136	788	0.612	2574
7321/9-1	559	1319	0.706	1.293	760	0.587	2591
Average							2774
Jurassic							
7321/7-1	1937	2027	1.654	1.698	90	0.044	4091
7321/8-1	1388	1477	1.364	1.424	89	0.060	2977
7321/9-1	1319	1364	1.293	1.325	46	0.032	2855
Average							3307
Upper Triassic							
7321/7-1	2057	3527	1.698	2.406	1470	0.692	4249
7321/8-1	1477	2835	1.424	2.127	1358	0.703	3865
7321/9-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average							4051

Table 2
Seismic resolution of 3D data.

Interval	Average velocity, v , [m/s]	Approximated dominant frequency (maximum frequency of dominant bandwidth), f [s^{-1}]	Wavelength, $\lambda=v/f$ [m]	Seismic resolution, $\lambda/4$ [m]
Cretaceous	2774	50–70	55–40	17–10
Jurassic	3307	40–45	83–73	18–21
Triassic	4051	40–45	101–90	25–23

Fig. 4. Composite seismic profile showing seismic tie to exploration well 7321/7-1. Seismic packages that are barely within seismic resolution on the highs relate to expanded packages in the basin. Inset shows lowermost Cretaceous, Jurassic and uppermost Triassic succession where four unconformities within 150 m are interpreted from biostratigraphic and petrophysical log data (Robertson Group, 1989). Seismic line bend indicated by vertical line. Location of seismic line is shown in Fig. 1c. Abbreviations: iIN: intra lower Norian, OC: Oxfordian-Callovian, BT: Berriasian-Tithonian, iuH: intra upper Hauterivian, iB: intra Barremian, iIA: intra lower Aptian, iA1: intra Aptian 1, iA2: intra Aptian 2, ilaI: intra lower Albian, lmaA: lower-middle Albian. Seismic data courtesy of TGS.

northern segment is oriented NNE-SSW (Fig. 1). Maximum displacement of the Berriasian-Tithonian horizon by 600 ms TWT (ca. 830 m) to 700 ms TWT (ca. 970 m) in the Fingerdjupet Subbasin is observed where the two fault segments branch. In the Randi Fault Set, fault displacement is generally smaller than 250 ms TWT (ca. 350 m) (Figs. 2 and 7). NNE-SSW faults defining large fault blocks in

the Bjørnøya Basin displace the Berriasian-Tithonian by between 500 and 600 ms TWT (ca. 700–830 m) (Fig. 1c). The NNE-SSW fault segments truncating the Berriasian-Tithonian horizon are straight to slightly curved. There are, however, some en echelon fault segments with various degree of linkage, from soft-links via relay ramps to hard-links (Fig. 1c, north of the Terningen Fault Complex).

Fig. 5. Seismic stratigraphic framework of the Late Triassic to Albian succession of the Fingerdjupet Subbasin. The Jurassic and Cretaceous basin evolution is the main focus of the present work and for the Norian to Middle Jurassic (~218–168 Ma), which in the study area corresponds to a relatively thin sedimentary package, is therefore hidden in the chronostratigraphy column. Chronostratigraphic chart modified from Gradstein et al. (2012).

The large west-facing NNE-SSW faults in the Bjørnøya Basin define the boundaries between large rotated fault blocks (Figs. 1 and 2). Stratigraphy of Carboniferous or older to Early Cretaceous age is affected by NNE-SSW faults in the Bjørnøya Basin and Fingerdjupet Subbasin (Fig. 2). The faults are occasionally truncated by the Upper Regional Unconformity (Base Quaternary).

Wedge-shaped seismic packages thickening towards faults trending NNE-SSW can be observed between several interpreted stratigraphic surfaces in the study area: Intra Permian to Middle Triassic (Fig. 2), Berriasian-Tithonian to intra upper Hauterivian (Fig. 6, Sequence 3) and intra Barremian to intra lower Albian (Fig. 6, Sequence 5). The Lower Cretaceous wedges can be seen in seismic sections in Figs. 7 and 8. Along strike of the Terningen Fault Complex, local transverse folds are observed between the Berriasian-Tithonian and intra lower Albian horizons (Fig. 9). These anticlines and synclines with fold axis orthogonal to fault strike suggest fault displacement maxima and minima related to relay zones (Fig. 9).

4.2. N-S faults

The large west-facing Leirdjupet Fault Complex, defining the eastern boundary of the Bjørnøya Basin and western boundary of the Ringsel Ridge, is one of few but prominent N-S striking extensional fault arrays in the study area. As seen in Fig. 1, this fault complex link up with a large NNE-SSW fault west of the shallow stratigraphic borehole 7320/3-U-1 via a number of en echelon fault segments striking approximately NNW-SSE. Vertical displacement of the Berriasian-Tithonian horizon over the Leirdjupet Fault Complex decreases from approximately 2500 ms TWT (ca. 3470 m) in the southern part of the study area to less than 190 ms TWT (ca. 260 m) 60 km farther north. Fault activity is displayed by several Lower Cretaceous wedge-shaped packages in the Bjørnøya Basin, which thicken towards the Leirdjupet Fault Complex (Figs. 2 and 8).

4.3. E-W faults

A fault population striking approximately E-W is observed throughout the study area (Fig. 1c). Compared to the previously

described fault systems, fault displacements of the Berriasian-Tithonian horizon are relatively modest, commonly in the range of 10–100 ms TWT (ca. 10–140 m) but locally up to 180 ms TWT (ca. 250 m). For the Berriasian-Tithonian horizon, individual faults are straight and can be traced along strike for up to 25 km. In the Fingerdjupet Subbasin and the eastern Bjarmeland Platform the displacement is for the most part less than 100 ms TWT (ca. 140 m), affecting Upper Triassic to Lower Cretaceous stratigraphy. The E-W oriented faults generally tip out down section in the lower part of the Upper Triassic interval. Minor growth packages towards E-W oriented faults are observed between the intra lower Norian and Oxfordian-Callovian horizons (Fig. 6, Sequence 1). The E-W oriented faults have also been active at a later stage, as indicated by fault displacements of the lower-middle Albian and upper Albian surfaces (Fig. 10). With faults mostly truncated at the URU, and absence of associated growth wedges in the preserved Lower Cretaceous section, dating of this fault activity is difficult. However, it certainly post-dates the early Albian.

4.4. NW-SE faults

An extensive system of NW-SE striking faults is observed in the 3D dataset. The fault system can be seen in seismic sections in Figs. 7 and 8 and in variance attribute maps for the lower-middle Albian and upper Albian horizons in Fig. 10. Maximum displacement is seen near the intra Lower Albian and lower-middle Albian horizons. Fault displacement varies from approximately 25 ms TWT (ca. 40 m) to near seismic resolution (17–10 m; Table 2) for the lower-middle Albian horizon. In seismic sections, the fault plane characteristics vary from virtually transparent to strongly reflective, with reflective faults traceable across the Fingerdjupet Subbasin. Timing of the fault activity is problematic as no growth wedges are observed and many faults are truncated at the URU. Fig. 10b shows how the upper Albian horizon, which is the uppermost interpretable Lower Cretaceous horizon in the Fingerdjupet Subbasin, is affected by the NW-SE fault system. The largest vertical displacements are seen near the intra lower Albian to lower-middle Albian horizons and the faults either tip out in the lower Albian or Aptian, or they interfere with the upper fault tips of deeper-seated

Fig. 6. Time thickness maps and seismic sections for sequences 1, 2, 3, 4, 5A and 5B. Wedge-shaped seismic packages consistent with syn-tectonic deposition are seen for sequences 1 (Intra lower Norian – Oxfordian-Callovian), 3 (Berriasian-Tithonian – intra upper Hauterivian) and 5 (Intra Barremian – intra lower Albian). Red arrows indicate thickness variations for the sequences. Seismic profile locations are indicated in the respective time thickness maps. Seismic data courtesy of TGS.

Fig. 7. Seismic profile showing the Triassic to Lower Cretaceous succession of the Fingerdjupet Subbasin. Colour overlays correspond to interpreted sequences as outlined in Fig. 5. Wedge-shaped seismic packages and pronounced thickness differences between the Fingerdjupet Subbasin and the Ringsel Ridge are seen for sequences 3 (BT – iuH) and 5 (iB – iIA). The strong, cross-cutting reflections seen in the upper part of the section, particularly near the Ringsel Ridge, are NW-SE oriented faults cut along strike by the seismic profile. Profile location is given in Fig. 1c. Seismic data courtesy of TGS.

Fig. 8. Seismic profile showing the northern Bjørnøya Basin and the Fingerdjupet Subbasin separated by the Ringsel Ridge. The Leirdjupet Fault Complex marks the western boundary of the Ringsel Ridge while the Terningen Fault Complex marks the eastern boundary. Colour overlays correspond to interpreted seismic sequences (Fig. 5). Sequences 3 (BT – iuH) and 5 (iB – iIA) show wedge-shaped seismic geometries in the Fingerdjupet Subbasin and the Bjørnøya Basin and pronounced thickness differences compared to the Ringsel Ridge. Profile location is seen in Fig. 1c. Seismic data courtesy of TGS.

faults, sometimes resulting in a significantly higher fault density such as above NNE-SSW faults in the Randi Fault Set (Fig. 7). Fault interaction is indicated by curved fault intersections with mainly E-W faults but also with the upper part of the Terningen Fault Complex (Fig. 10).

5. Basin architecture

The Upper Triassic to recent strata present in the Fingerdjupet Subbasin have been divided into seven sequences. Results from the seismic interpretation are shown on seismic sections in Figs. 2 and

6–8, and as a time-structure map for the Berriasian-Tithonian horizon in Fig. 1. Fig. 5 presents a summary of the mapped seismic horizons and how they relate to chronostratigraphy, observed seismic geometries and thereby sequences. An overview of thickness variations for Sequences 1, 2, 3, 4, 5A and 5B is presented in Fig. 6. Wedge-shaped seismic geometries pre-dating the Late Triassic are clearly seen in the Bjørnøya Basin and Fingerdjupet Subbasin in Fig. 2, however, detailed description of these is beyond the scope of this work; information is given in Kamp (2016). Lower to Middle Triassic deltaic deposits have a substantial thickness in the Hoop Fault Complex but pinch out or condense rapidly W

Fig. 9. Seismic section showing transverse folds related to fault displacement gradients and relay zones in the Terningen Fault Complex. Profile is taken along strike and close to a large fault in the hangingwall of the Terningen Fault Complex. Location of seismic line is shown in Fig. 1c. Seismic data courtesy of TGS.

Fig. 10. Variance attribute draped on lower-middle Albian horizon (10a) and upper Albian horizon (10b) highlighting fault trends affecting the Albian succession. Dominant fault populations are oriented NW-SE and NNE-SSW with a minor influence from E-W oriented faults. Seismic data courtesy of TGS.

towards the Fingerdjupet Subbasin (Fig. 2).

5.1. Sequence 1: Intra lower Norian to Oxfordian-Callovian (ilN-OC)

Sequence 1 shows a general westward increase in thickness, from 40 to 120 ms TWT (ca. 70–200 m). The thickest part of the sequence is seen on the Ringsel Ridge (Figs. 7 and 8). In the Fingerdjupet Subbasin, smaller-scale time-thickness variations are observed as wedge-shaped seismic packages with 20–30 ms TWT (ca. 30–50 m) thickness increase towards E-W oriented faults (Fig. 6, Sequence 1). In the northern part of the study area, the sequence locally increases in thickness towards the top of the

footwall blocks of faults oriented NNE-SSW.

5.2. Sequence 2: Oxfordian-Callovian to Berriasian-Tithonian (OC-BT)

Sequence 2 varies in thickness between 10 and 70 ms TWT (ca. 20–120 m). There is a general westwards thickness increase and a small but distinct thickness increase is observed along a smooth, gently curved, northeast to north oriented line through the study area (Fig. 6-Sequence 2). The sequence does not seem to change thickness neither across faults oriented E-W nor the N-S to NNE-SSW oriented faults in the Terningen Fault Complex.

5.3. Sequence 3: Berriasian-Tithonian to intra upper Hauterivian (BT-iuH)

Sequence 3 is characterized by wedge-shaped seismic packages, where there is a thickness increase towards NNE-SSW striking normal faults (Fig. 6–Sequence 3, Figs. 7 and 8). The thickness varies from approximately 200 ms TWT (ca. 280 m) close to the Terningen Fault Complex to 20 ms TWT (ca. 30 m) along the eastern margin of the basin. Wedge-shaped seismic packages thicken both towards the Terningen Fault Complex and towards faults bounding individual rotated fault blocks within the Fingerdjupet Subbasin and the Randi Fault Set. This fault array with associated sedimentary growth packages is shown in a seismic section in Fig. 7 and in a Berriasian-Tithonian time-structure map in Fig. 1. Sequence 3 reflectors are cut by faults while onlapping the hangingwall dipslopes (Fig. 7). No significant erosion of the footwall highs has been observed. Locally, E-W striking faults appear to have an influence on thickness variation observed in the data as seen in the time-thickness map (Fig. 6, Sequence 3).

5.4. Sequence 4: Intra upper Hauterivian to intra Barremian (iuH-iB)

Sequence 4 varies in thickness from 200 to 500 ms TWT (ca. 280–700 m). In the Ringsel Ridge the top of the sequence has been truncated by the intra Barremian horizon and 200–250 ms TWT thickness (ca. 280–350 m) is recorded (Fig. 7). In the Fingerdjupet Subbasin the thickness varies between 350 and 400 ms TWT (ca. 490–560 m). Along the eastern flank of the Fingerdjupet Subbasin the sequence records a time-thickness between 420 and 500 ms TWT (ca. 580–690 m) and on the Bjarmeland Platform in the eastern part of the study area the thickness is 350–400 ms TWT (ca. 490–560 m). The thickness variations of Sequence 4 occur across NNE-SSW and N-S trending faults; mainly for the Terningen Fault Complex but also across faults with less displacement in the Randi Fault Set. The sequence shows two oppositely directed systems of prograding clinoforms (Figs. 11 and 12). SE prograding clinoforms (Fig. 11) are most easily observed on the platform east in the study area where the succession is relatively flat-lying, the fault density is low and the present burial depth is shallow. This system can also be observed in the Randi Fault Set, where detailed correlation is made

difficult by densely spaced NNE-SSW faults, and in the Fingerdjupet Subbasin, although the level of detail is lower than on the Bjarmeland Platform because of the greater burial depth (Fig. 7). In the southeastern part of the study area, on the Bjarmeland Platform, the SE prograding clinoform system merges with and overlies another system of clinoforms displaying a NW direction of progradation and steeper foreset angles (Fig. 12). The clinoform systems are overlain by a conformable succession of laterally continuous, parallel reflections. The top of this succession shows a varying degree of erosional truncation at the intra Barremian horizon.

5.5. Sequence 5: Intra Barremian to intra lower Albian (iB-ilAl)

Sequence 5 shows pronounced wedge-shaped geometries and thickening of seismic packages towards NNE-SSW faults in the

Fig. 12. Seismic profile showing two separate systems of prograding clinoforms in Sequence 4 (Fig. 5) on the Bjarmeland Platform. The low-angled, southeast prograding clinoforms correspond to the system seen in Fig. 11. The seismic line azimuth represents depositional dip for both systems. Location of profile is seen in Fig. 1c. Seismic data courtesy of TGS.

Fig. 11. Seismic profile showing prograding clinoforms of Sequence 4 (Fig. 5) in the Randi Fault Set and on the Bjarmeland Platform. The clinoforms show a SE direction of progradation. Location of profile is shown in Fig. 1c. Seismic data courtesy of TGS.

study area (Figs. 2, 7 and 8, 6-sub-sequences 5A and 5B). In the most prominent Lower Cretaceous Fingerdjupet depocenters the sequence reaches thicknesses of approximately 600 ms TWT (ca. 830 m), while it thins towards the platform in the east to less than 50 ms TWT (ca. 70 m). From the base to the top of sequence 5 there is a marked change in which faults control the distribution of sediments, as indicated in Fig. 5. Sequence 5 has therefore been divided into two sub-sequences.

5.5.1. Sub-sequence 5A: Intra Barremian to intra Aptian 1 (iB–iA1)

Sub-sequence 5A is characterized by pronounced thickening towards the Terningen Fault Complex and several other smaller faults in the Randi Fault Set, strengthening the half-graben versus footwall high morphology across the Fingerdjupet Subbasin (Fig. 7). The sub-sequence is not present in the Ringsel Ridge, where the intra Barremian horizon can be seen truncating parts of sequence 4 (Fig. 13b). Sub-sequence 5A onlaps the intra Barremian horizon at individual footwall highs in the Randi Fault Set as well as the eastern margin of the Fingerdjupet Subbasin. The intra lower Aptian horizon (internal to sub-sequence 5A) locally truncate strata of the lower part of sub-sequence 5A east in the Fingerdjupet Subbasin and in the Randi Fault Set (Fig. 13c). Wedge-shaped seismic packages deposited roughly contemporaneously with this sub-sequence are observed in the hangingwall of the Leirdjupet Fault Complex in the Bjørnøya Basin (Figs. 2 and 8). The intra Aptian 1 horizon (base sub-sequence 5B) is the first horizon to blanket both the Ringsel Ridge and the Randi Fault Set (Figs. 7, 8 and 13).

5.5.2. Sub-sequence 5B: Intra Aptian 1 to intra lower Albian (iA1–iAl)

Sub-sequence 5B drapes the Randi Fault Set but shows a significant thickening towards the Terningen Fault Complex. Progressively smaller time-thickness differences between the main Fingerdjupet Subbasin depocenter and the adjacent Ringsel Ridge are observed up section (Figs. 7 and 8). In the Ringsel Ridge the thickness of sub-sequence 5B varies between 150 and 200 ms TWT (ca. 210–280 m) whereas in the Fingerdjupet Subbasin the thickness reaches 300 ms TWT (ca. 420 m).

5.6. Sequence 6: Intra lower Albian to Upper Regional Unconformity (iAl–URU)

The Albian strata of the Fingerdjupet Subbasin are truncated by the URU. Accordingly, thickness variations of sequence 6 are strongly affected by uplift and erosion, which have removed progressively older strata towards the basin margins (Figs. 7 and 8).

The lower parts of sequence 6, from intra lower Albian to lower-middle Albian, are present in most parts of the basin and record a slight, gradual westward thickening. The sequence onlaps the eastern basin margin until Upper Albian strata drape the western Bjarmeland Platform. No thickness variations associated to any fault trends are observed, but the package has been offset by NNE–SSW, NW–SE and E–W oriented fault systems after deposition (Fig. 10).

5.7. Sequence 7: Upper Regional Unconformity to seabed (URU–Sb)

Sequence 7 consists of Quaternary deposits with common SW–NE oriented iceberg plough marks at the seabed. The lower boundary surface is the URU, which separates the sequence from the underlying Lower Cretaceous deposits. The time-thickness of the sequence varies between approximately 70 ms TWT in the southwest to practically zero in the northwest towards the Stappen High. Seismic sections in Figs. 2, 7 and 8 show the URU eroding deeply into the Albian strata in the Fingerdjupet Subbasin.

6. Discussion

We aim at establishing a seismic- and tectonostratigraphic framework for the Jurassic to Lower Cretaceous strata of the Fingerdjupet Subbasin; however, reactivation of previously established tectonic fabrics seems obvious and calls for a short discussion on inheritance and larger-scale structure. The results presented in chapters 4 and 5 are subsequently discussed in a western Barents Sea context to assess the regional significance of observations from the Fingerdjupet Subbasin.

6.1. Local inheritance and reactivation

The Terningen Fault Complex is a fundamental structure that controls accommodation space creation in the Fingerdjupet Subbasin. Sedimentary growth packages suggest deposition during periods of active extensional faulting as illustrated in Figs. 5–8. On a large scale, the Fingerdjupet Subbasin can be seen as a semi-regional rollover structure where the Bjarmeland Platform rolls into the Terningen Fault Complex. Extension is accommodated by displacement on the Terningen Fault Complex that changes/link into an underlying lower-angle detachment fault at depth (Fig. 2, ~5 s TWT). This seismically mappable fault geometry gives a listric expression that offers a viable explanation for the overlying rollover fold (e.g. Hongbin Xiao and Suppe, 1992). Closely spaced sub-parallel faults in the Randi Fault Set may either represent

Fig. 13. Seismic sections showing truncation of seismic reflections in the Ringsel Ridge (a, b) and uplifted footwall highs in the Fingerdjupet Subbasin (c). Locations of seismic profiles are given in Fig. 1c. Seismic data courtesy of TGS.

breakdown faults in the rollover, with antithetic and synthetic faults rooted in the deeper detachment, or outer-arc extension faults in the rollover anticline (Figs. 1c and 2). Extensional faults in the crest of rollover anticlines have been demonstrated on a variety of scales from seismic data to analogue experiments (e.g. Hongbin Xiao and Suppe, 1992; Mauduit and Brun, 1998; McClay, 1990).

Extensional faulting likely reactivated the underlying structural grain of Caledonian contractional structures (Barrère et al., 2009; Blaich et al., 2017; Gernigon et al., 2014; Gernigon and Brönnner, 2012; Ritzmann and Faleide, 2007), which has been described on Bjørnøya by Braathen et al. (1999b) and Worsley et al. (2001). There, Caledonian thrusts were reactivated as normal faults in the Carboniferous, resulting in syn-tectonic deposition mainly related to N-S striking faults. Blaich et al. (2017) mapped mid-Carboniferous growth packages linked to NE-SW striking faults in the northern Bjørnøya Basin and southern Stappen High. Wedge-shaped seismic packages of pre-Permian age have not, however, been observed in the Fingerdjupet Subbasin. Although beyond the scope of this work, it is worth noting that syn-extensional deposits related to low-angle detachment faults might display different geometries than the typical wedge-shaped seismic geometries related to steeply dipping normal faults (Friedmann and Burbank, 1995; Peron-Pinvidic et al., 2007). Hence, Carboniferous (and/or Devonian) extension might have affected the Fingerdjupet Subbasin even though there are no observable growth packages in the assumed pre-Permian stratigraphy. Speculatively, pre-Late-Permian extension in the Fingerdjupet Subbasin may have been accommodated by extensional reactivation of Caledonian thrust faults, perhaps represented by e.g. the proposed low-angle detachment in Fig. 2 (~5 s TWT). The steeply dipping Terningen Fault Complex, which has been instrumental for the current basin architecture, was then established in the Late Permian. The Leirdjupet Fault Complex was also active in the Late Permian to Early Triassic, leading to deposition of growth packages in the Bjørnøya Basin described by Blaich et al. (2017) and evident in Fig. 2. The age of this faulting is constrained by seismic tie to well 7321/8-1 in the southern Fingerdjupet Subbasin ("Norwegian Petroleum Directorate Factpages," 2017).

Reactivation in the Terningen Fault Complex is suggested as a fundamental control on Fingerdjupet Subbasin evolution based on the confident observation of growth packages in Late Permian–Early Triassic strata (Kamp, 2016), in sequences 3 and 5 (Figs. 2, 6–8), descriptions of Late Triassic growth wedges connected to the Terningen Fault Complex (Kamp, 2016), and evidence for extensional faulting post-dating the youngest preserved basin fill. Based on the current work and observations by Blaich et al. (2017) it is suggested that the Bjørnøya Basin and Fingerdjupet Subbasin shares a common history of reactivation of major, steeply dipping N-S and NNE-SSW faults from the Late Permian onwards. Orientation of faults may not fully reflect the stress regime at the time of faulting, especially if basement rooted with a strong inherited trend (Sibson, 1985). Depending on changes in the stress regime, reactivation could be favored over establishing new trends, as would be expected for the Terningen Fault Complex and Randi Fault Set. On the other hand, E-W and NW-SE fault sets, which are confined to intervals in the stratigraphy, more likely represent the stress field driving the faulting. It follows from this that significant changes in the local stress regime have occurred several times in basin history, notably (1) between Late Triassic reactivation of the NNE-SSW Terningen Fault Complex (Kamp, 2016) and latest Triassic to Middle Jurassic faulting in the E-W striking fault population; (2) between cessation of extensional faulting in the E-W oriented fault population in the Middle Jurassic and another reactivation of the Terningen Fault Complex in the latest Jurassic to Hauterivian; and (3) during one or several periods in post-Albian times as evident by faulting along

NW-SE striking faults and reactivations of NNE-SSW, N-S and E-W striking fault populations. Although further evidence is needed, these inferred changes in the local stress regime are believed to reflect the interplay between North Atlantic and Arctic extensional tectonics as previously suggested by e.g. Faleide et al. (1993b).

6.2. Basin evolution

6.2.1. Latest Triassic to Middle Jurassic extensional faulting

Sequence 1 (intra lower Norian – Oxfordian-Callovian) records an extensional faulting event in the Fingerdjupet Subbasin where growth wedges relate to faults oriented E-W (Fig. 6-Sequence 1). Previous work by Faleide et al. (1993a, 1993b, 2015) and Gabrielsen et al. (1990) have briefly touched upon Jurassic extensional faulting events affecting the Fingerdjupet Subbasin, although limitations in seismic coverage and resolution have made it difficult to decide on the timing of these events and also whether the extensional faulting events were continuous or punctuated by tectonically quiet periods. Faleide et al. (1993a, 1993b) linked a Bathonian/Callovian hiatus in the Hammerfest Basin to the onset of Middle-Late Jurassic tectonics in the Barents Sea and indicated that this tectonic phase likely initiated the subsidence of the Bjørnøya Basin. For the present study, seismic resolution still represents a challenge for deciding on the timing of the extensional faulting event recorded by Sequence 1. This is illustrated by Fig. 4 (inset), where unconformities inferred from biostratigraphic and petrophysical log data are closely spaced in the seismic data. More specific age constraints on this extensional faulting event must be inferred from wells, where the stratigraphic resolution is much higher. One indication for the timing of faulting is an unconformity interpreted from biostratigraphic and petrophysical log data of well 7321/7-1 (Robertson Group, 1989) where Bathonian to middle Bajocian strata are likely to be absent. This hiatus could reflect vertical movements in the area, triggered by faulting, consistent with a late Middle Jurassic rift event. Collanega et al. (2017) suggested E-W faults in the Hoop Fault Complex area were active in the Early Jurassic. Judging from the expansion of strata towards E-W oriented faults in the Fingerdjupet Subbasin; however, faults were likely active also in the latest Triassic (Norian). Higher resolution data will be needed to decide whether the extension was continuous throughout deposition of Sequence 1 or if the observed growth packages result from several phases of extensional faulting. Unconformities within Sequence 1 inferred from well 7321/7-1 (Middle Norian-Rhaetian/upper Norian and Bathonian-middle Bajocian inferred absent) (Robertson Group, 1989) suggest the latter. Observations from Edgeøya and Hopen in the northern Barents Sea (Osmundsen et al., 2014) and the Goliat area of the Hammerfest Basin in the southern Barents Sea (Mulrooney et al., 2017) are consistent with observations from the Fingerdjupet Subbasin and indicate the regional significance of extensional faulting in E-W striking faults commencing in the Norian. The interpreted Oxfordian-Callovian surface marks the cessation of activity on E-W striking faults in the Fingerdjupet Subbasin, thus disagreeing with the Late Jurassic faulting inferred by Gabrielsen et al. (1990) and Faleide et al. (1993a) both in terms of fault timing and which fault trends were active.

The thickness increase observed locally towards the top of the footwalls of NNE-SSW faults is enigmatic, although seismic interpretation suggests these faults were not active during deposition of sequence 1 (Fig. 6, Sequence 1). Possible explanations include differential compaction where the uplifted footwall was compacted less than the adjacent basin, and/or hydrocarbon-filled sandstones at the crests of rotated fault blocks causing velocity pull-down.

6.2.2. Late Jurassic tectonic quiescence

Sequence 2 (Oxfordian-Callovian – Berriasian-Tithonian) is

largely undisturbed by the different fault sets present in the Fingerdjupet Subbasin. There is a slight but marked westward thickness increase that can be followed along a smooth, gently curved line for more than 100 km (Fig. 6, Sequence 2). This feature crosses both the NNE-SSW Terningen Fault Complex and many of the E-W oriented faults with no affiliated thickness variations, suggesting the faults were not active upon deposition of Sequence 2. Hence, the westward thinning trend likely has a sedimentary rather than tectonic origin. It is thus considered unlikely that the Late Jurassic tectonism has generated the main (N-S/NNE-SSW) fault trend of the Fingerdjupet Subbasin as previously suggested by Gabrielsen et al. (1990) and Faleide et al. (1993a). This deviates from observations in the Hammerfest Basin, where the Late Jurassic to Early Cretaceous records the culmination of Mesozoic rifting which started in Middle Jurassic times (e.g. Faleide et al., 1993b). Speculatively, a greater part of the SW Barents Sea area, including the Fingerdjupet Subbasin, the western Bjarmeland Platform with the Hoop Fault Complex and Mercurius High (Collanega et al., 2017), and the Hammerfest Basin (Faleide et al., 1993b; Gabrielsen et al., 1990; Indrevær et al., 2016; Mulrooney et al., 2017) experienced Early to Middle Jurassic extensional faulting on E-W faults, while deformation became localized to the Hammerfest Basin as extension persisted through the Late Jurassic to Early Cretaceous. Blaich et al. (2017) suggested a Late Jurassic extensional event affected the Bjørnøya Basin and Fingerdjupet Subbasin, leading to deposition of Kimmeridgian-Tithonian growth packages along major NE-SW and NNE-SSW faults. Detailed 3D mapping performed for the current work, however, does not support these conclusions; thickness differences in Late Jurassic strata in the Fingerdjupet Subbasin seem unrelated to any fault trends. We therefore conclude that tectonic quiescence prevailed in the Fingerdjupet Subbasin in the Late Jurassic. It can thus be speculated that the influence of North Atlantic tectonics reached the Bjørnøya Basin at this time, but not further east into the Fingerdjupet Subbasin.

6.2.3. Latest Jurassic to Hauterivian extensional faulting

Sequence 3 (Berriasian-Tithonian – intra upper Hauterivian) is clearly affiliated with N-S to NNE-SSW faults, where growth wedges relate to the Terningen Fault Complex and faults in the Randi Fault Set (Fig. 6-Sequence 3, Figs. 7 and 8). Growth wedges that occupy the approximately same stratigraphic position in the Bjørnøya Basin are observed banked onto the Leirdjupet Fault Complex and other large NNE-SSW faults in the basin. This is supported by Blaich et al. (2017), who suggested a Valanginian-Hauterivian extensional phase affected the Bjørnøya Basin, southern Stappen High and Fingerdjupet Subbasin. The Hoop Fault Complex to the east of the study area likely also experienced extension at this time (Fitriyanto, 2011), indicating the semi-regional significance of an extensional faulting event (Figs. 2 and 8). The growth packages related to this faulting have a significantly larger areal extent and time thickness compared to those of the proposed latest Triassic – Middle Jurassic extensional faulting event in the Fingerdjupet Subbasin, thus suggesting both larger sediment supply and that a higher relief bathymetry was generated. Considering there was sedimentation on the uplifted footwall highs in the Randi Fault Set it is suggested that Sequence 3 was deposited in a fully marine environment. This is supported by observations of a Valanginian to Barremian condensed section with overlying middle Barremian marine clays in a shallow stratigraphic corehole (7320/03-U-01) on the northern Ringsel Ridge (Smelror et al., 1998; Århus and Kelly, 1990).

Based on the observations from Sequence 3, a latest Jurassic to Hauterivian extensional faulting event is proposed for the Fingerdjupet Subbasin. This extension by movement on N-S to NNE-SSW faults must represent a change in the local stress regime from the

suggested latest Triassic to Middle Jurassic extensional faulting event, when the area experienced activity along E-W oriented faults. The inferred stress-axis change might relate to an increasing influence of rifting in the North Atlantic relative to the Arctic around the Jurassic-Cretaceous transition as previously suggested by Faleide et al. (2008, 1993b). This led to reactivation of major fault complexes such as the Ringvassøy-Loppa Fault Complex, Bjørnøyrenna Fault Complex and Leirdjupet Fault Complex (Blaich et al., 2017; Faleide et al., 1993b).

6.2.4. Hauterivian to Barremian tectonic quiescence and clinoform deposition

Sequence 4 is characterized by the presence of prograding clinoforms on the Bjarmeland Platform, in the Randi Fault Set and in the Fingerdjupet Subbasin (Figs. 7, 8, 11 and 12). The dominant SE direction of progradation seen in Fig. 11 on the western edge of the Bjarmeland Platform implies that the system must have travelled past the Randi Fault Set area. With distinct, stepwise thickness increase of the sequence in the Randi Fault Set, the prograding system must have interacted either with active faults or with a fault-controlled topography resulting from earlier events that created an under-filled sink. No apparent growth wedges are observed in Sequence 4 at the bottom of the grabens and half-grabens of the Randi Fault Set. Accordingly, we suggest the prograding system filled relict and underfilled fault bathymetry before advancing further southeast. This contrasts Faleide et al. (1993a, 1993b), who speculated that a Hauterivian/Barremian tectonic event indicated from wells in the Hammerfest Basin should have more strongly affected the Bjørnøya Basin. No clinoform geometries are observed in the Ringsel Ridge, suggesting it was a positive bathymetric feature bounded by areas of deeper water as the prograding system entered the study area, perhaps as a result of footwall uplift on the Leirdjupet and Terningen fault complexes during the suggested latest Jurassic to Hauterivian extensional faulting event. The SE prograding clinoform system merges with and overlies NW prograding clinoforms on the western Bjarmeland Platform (Fig. 12), thus indicating the presence of an uplifted source area to the south. Different foreset angles might represent differences in parameters related to the paleogeographic setting and grain size distribution (Patruno et al., 2015). The SE prograding system has an inferred source area NW to W of Svalbard, commonly linked to regional uplift on the northern Barents margin related to the HALIP (Faleide et al., 2015, 1993b; Marin et al., 2016; Midtkandal et al., 2015; Midtkandal and Nystuen, 2009; Senger et al., 2014). The long distance to the inferred source area suggests dominantly fine-grained sediments are expected, supported by descriptions of the section in wells 7321/7-1, 7321/8-1 and 7321/9-1 ("Norwegian Petroleum Directorate Factpages," 2017; Robertson Group, 1989) and consistent with gently dipping clinoforms observed in seismic data in the Fingerdjupet Subbasin and western Bjarmeland Platform. Some caution must be exercised, however; Hinna (2016) observed clinoforms pinching out before reaching the well locations (7321/7-1, 7321/8-1 and 7321/9-1). The exploration wells targeted rotated fault blocks along NNE-SSW to N-S faults which were active during the latest Jurassic to Hauterivian extensional faulting event and with associated footwall uplift. The rotated fault blocks may thus have represented bathymetric highs as the clinoform system prograded into the area. Hence, the deposits described in the wells might not fully represent the SE-prograding clinoform system. The steeper foreset angles in the NW prograding system indicate a more proximal position with regards to source area, which together with the Barremian age of the sequence, supports an Early Barremian uplift of the Loppa High as described by Indrevær et al. (2016). Though proximal to the Loppa High, no inversion structures related to this uplift are observed in the study

area.

6.2.5. Aptian extensional faulting

Sequence 5 (intra Barremian – intra lower Albian) records a significant extensional faulting event where growth packages are observed along N-S and NNE-SSW oriented faults. They link up with faults active during the proposed Tithonian to Hauterivian extensional faulting event, thus suggesting reactivation as a control on basin development (Fig. 6–Sequence 5). The sequence follows a typical fault system evolution where many faults are involved in the initial nucleation phase but eventually all the extension is focused on a few large faults (Fig. 6–sub-sequence 5A and 5B) (Cowie, 1998). Sub-sequence 5A (intra Barremian – intra Aptian 1) shows growth packages along many faults in the Terningen Fault Complex and the Randi Fault Set, setting up a basin-wide morphology of half-grabens and footwall highs (Fig. 6–sub-sequence 5A, Fig. 7). Sub-sequence 5A is not present on the Ringsel Ridge, possibly as a consequence of footwall uplift in the Terningen and Leirdjupet fault complexes early during the this extensional faulting event, causing subaerial exposure and erosion of Barremian strata. Truncation of strata internally in Sub-sequence 5A in uplifted footwall blocks in the Randi Fault Set suggests some subaerial exposure in the early Aptian, although erosion of these footwall highs was shallower than for the Ringsel Ridge (Fig. 13). The Robertson Group (1989) interpreted marine claystones above and below the intra Aptian 1 surface from cuttings and sidewall cores in well 7321/7-1, suggesting the footwall highs were drowned during continued extensional faulting and deposition of sub-sequence 5B.

The base of sub-sequence 5B marks the end of extensional faulting in the Randi Fault Set as the sub-sequence drapes the footwall highs. A significant thickening towards the Terningen Fault Complex suggests this structure offers the main control on the sediment sink for sub-sequence 5B. The variations in thickness observed across the Terningen Fault Complex decrease up sequence until no difference is observed near the intra Lower Albian horizon, indicating decreasing displacement rates on the controlling faults and/or infill of fault morphology after the end of faulting.

While Sequence 5 contains Barremian to lower Albian strata, an Aptian timing of extensional faulting is suggested on the basis of (1) the deep erosion into Barremian strata in the Ringsel Ridge (Figs. 4 and 13); (2) the absence of sub-sequence 5A on the Ringsel Ridge, indicating an early Aptian extensional faulting climax with associated footwall uplift in the Terningen Fault Complex (Figs. 4, 7, 8 and 13); and (3) decreasing time thickness differences across the Terningen Fault Complex through the Aptian, with only minor differences for the possible lower Albian strata near the top of sub-sequence 5B (Figs. 4, 7 and 8). Faleide et al. (1993a, 1993b) and Blach et al. (2017) described an Aptian rift event in the Bjørnøya Basin, Fingerdjupet Subbasin and southern Stappen High, where the Ringsel Ridge experienced uplift and erosion. These observations are consistent with the present study, where Barremian strata in the Ringsel Ridge are truncated (Fig. 13) and the unconformity correlates with growth wedges in the Fingerdjupet Subbasin and Bjørnøya Basin (Figs. 2, 7 and 8). The extent and thickness of these growth wedges, however, cannot be accounted for by erosion of the Ringsel Ridge alone and indicate additional sediment sources were present.

The Barremian-earliest Aptian magmatism on Svalbard and the shelfal areas to the E and S, seen as flood basalts and intrusive dykes and sills and described by e.g. Grogan et al. (2000), Maher (2001), Minakov et al. (2012) and Polteau et al. (2016), follows a NNE grain. The magmatism on Svalbard and Franz Josef Land is suggested to result from a distinct magmatic event at 125 Ma (Polteau et al., 2016), essentially contemporaneously with extensional faulting in the Terningen Fault Complex, Randi Fault Set and

Leirdjupet Fault Complex. This indicates a link to the Fingerdjupet Subbasin and Bjørnøya Basin where Aptian extension is evident as normal faulting with associated sedimentary growth packages in the Terningen Fault Complex, Leirdjupet Fault Complex and other faults. The extension across the entire western Barents shelf likely relates to the northward propagation of Atlantic rifting (Blach et al., 2017; Faleide et al., 2008, 1993b) while the manifestation of the extension, speculatively, might vary as a function of proximity to the HALIP. Atlantic influence on areas adjacent to the Fingerdjupet Subbasin is evident from documented extensional faulting in the Polhem Subplatform and the Ringvasøy-Loppa and Bjørnøyrenna fault complexes (Indrevær et al., 2016).

6.2.6. Albian tectonic quiescence and post-late Albian extensional faulting

Sequence 6 (intra lower Albian – URU) represents a conformable succession of Albian strata in the Fingerdjupet Subbasin. The Fingerdjupet Subbasin was still a sediment sink in the early Albian as indicated by onlaps onto the slope towards the Bjarmeland Platform, which was subsequently draped by upper Albian strata. Sequence 6 is offset by faults with orientations NNE-SSW, E-W and NW-SE (Figs. 7, 8 and 10). The timing of the tectonic events related to these faults, however, is difficult to constrain in the Fingerdjupet Subbasin both because of the lack of growth wedges related to the faults and also because the faults are commonly truncated at the URU. The post-Early Cretaceous development of the basin must be examined indirectly by studying neighboring basins where post-Lower Cretaceous deposits have been preserved. This is beyond scope for the present work. The orientations of the fault systems affecting Sequence 6 indicate not only reactivation of faults related to the proposed latest Triassic-Middle Jurassic and Barremian-lower Albian extensional faulting events, but likely also a change in the direction of extension leading to faulting along NW-SE oriented faults. The limited preserved stratigraphy and lack of confident observations of cross-cutting relationships makes it difficult to establish a sequence of events for the younger fault activity. It likely reflects varying stress regimes and fault styles during the Late Cretaceous and Paleogene extension leading to breakup and seafloor spreading in the Norwegian-Greenland Sea in the Eocene (Faleide et al., 2008).

7. Conclusions

- The Fingerdjupet Subbasin has an evolution closely linked to reactivation of a N-S to NNE-SSW extensional fabric established in the Late Permian possibly following thrusting and extensional collapse in the Caledonian Orogen in the Silurian and Devonian and an inferred Carboniferous extensional reactivation. The Bjørnøya Basin and Fingerdjupet Subbasin share a common history of extensional faulting and reactivation on steeply dipping N-S to NNE-SSW faults from the Late Permian onwards. The Fingerdjupet Subbasin evolved as a semi-regional rollover structure where the Bjarmeland Platform was repeatedly downfaulted in the Terningen Fault Complex, creating accommodation space in the hangingwall. The Randi Fault Set developed as a result of outer-arc extension and breakdown faulting in the crest of the rollover anticline.
- Extension led to normal faulting on E-W striking faults from the latest Triassic to late Middle Jurassic in the Fingerdjupet Subbasin and adjacent areas. This extensional faulting event likely affected a very large area, suggested by recent observations from other workers north (Edgeøya and Hopen) and south (Hammerfest Basin) in the western Barents Sea.

- Late Jurassic tectonic quiescence in the study area contrast Late Jurassic to earliest Cretaceous extensional faulting on E-W striking faults in the Hammerfest Basin.
- Reactivation in the Terningen Fault Complex, Randi Fault Set and other N-S and NNE-SSW faults in the latest Jurassic to Hauterivian established the Fingerdjupet Subbasin as a major Lower Cretaceous depocenter. The study area remained submerged through this phase of extensional faulting and the relief generated by faulting was not filled. The change in the local stress regime leading up to this extensional faulting likely relates to an increasing influence of rifting in the North Atlantic relative to the Arctic.
- During Barremian tectonic quiescence, SE prograding deltaic deposits derived from an uplifted region NW of Svalbard filled the Fingerdjupet Subbasin before prograding further SE on the Bjarmeland Platform. Early Barremian uplift of the Loppa High resulted in NW prograding clinoforms on the western Bjarmeland Platform.
- Reactivation of major fault complexes in the SW Barents Sea, including the Terningen and Leirdjupet fault complexes, occurred in the Aptian, leading to subaerial exposure of the Ringsel Ridge and footwall highs in the Randi Fault Set. Sedimentary growth wedges received sediments from these proximal sources as well as distal sources.
- Post-upper Albian extension led to both reactivation of E-W and N-S to NNE-SSW extensional fabrics and faulting along NW-SE striking faults, reflecting a changing stress regime during Late Cretaceous–Paleogene extension and subsequent breakup and seafloor spreading in the North Atlantic.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.marpetgeo.2017.06.044>.

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8.2. Article 2 – Extensional fault and fold growth: impact on accommodation evolution and sedimentary infill

Serck, C. S.¹ and Braathen, A.¹ (2019) 'Extensional fault and fold growth: impact on accommodation evolution and sedimentary infill', *Basin Research*. doi: 10.1111/bre.12353.

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8.3. Article 3 – From supradetachment to rift basin: continental to marine deposition in the Paleogene Bandar Jissah Basin, NE Oman.

Serck, C. S.¹, Braathen, A.¹, Olaussen, S.², Midtkandal, I.¹, Indrevær, K.¹, Osmundsen, P.T.³, Stemmerik, L.⁴, & van Yperen, A.E.¹ (in prep.). From supradetachment to rift basin: continental to marine deposition in the Paleogene Bandar Jissah Basin, NE Oman. *Prepared for submission to Basin Research*

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9. Appendix

9.1. Abstracts, first author

9.1.1. Serck et al. (2017). *International Meeting of Sedimentology, Toulouse.*

Serck, C.S.¹, van Yperen, A.E.¹, Braathen, A.¹, Midtkandal, I.¹, Olaussen, S.², Appleyard, T.² and Osmundsen, P.T.³ (2017). Carbonate-to-clastic sediment dynamics in a high-relief, supra-detachment basin: Continental to marine deposition in the Bandar Jissah Basin, NE Oman.

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Accepted for oral presentation

CARBONATE-TO-CLASTIC SEDIMENT DYNAMICS IN A HIGH-RELIEF SUPRA-DETACHMENT BASIN CONTINENTAL TO MARINE DEPOSITION IN THE BANDAR JISSAH BASIN, NE OMAN

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A close relation between fault movement and sedimentary stacking is evident from the tectonostratigraphic signature of the mostly Eocene Bandar Jissah Basin, near Muscat in the Sultanate of Oman. The basin evolved above a major extensional detachment linked to extensional collapse following the Late Cretaceous Oman ophiolite emplacement. The basin infill is exposed along excellent, kilometer-scale cliffs, revealing a ~1,5 km thick sedimentary succession in the hanging wall of a major segmented boundary fault locating roll-over folds. The Paleocene (?) to Eocene basin fill records extensional faulting episodes along two hard-linked, large normal faults striking NW and NE, respectively. Initial high input of coarse clastic material is considered a response to basin-bounding fault activity in a continental setting. A coarse conglomerate was deposited near the fault escarpment during the early stage of faulting, and grain size reduction away from the fault reflects increased distality. Conglomerates proximal to the fault represent alluvial fan and braid-plain deposits with scattered patches of preserved soil profiles that are otherwise eroded. Braid-plain deposits dominate with greater distance from the fault, while soil profiles increase in thickness and lateral extent. Sediment maturity and palaeocurrent data suggest a localized sediment source, presumably a canyon cut across the boundary fault. A thin transgressive lag marks the boundary between continental conglomerates and mixed carbonate/siliciclastic sandstones formed in a submarine setting. These mixed deposits are considered to represent an extensional faulting climax, where tectonic subsidence outpaced sedimentary input, thus effectively drowning most of the basin. Sediment supply caught up with tectonic subsidence during the late stage of this episode, as evident by a shallowing-upward signature in the carbonate/siliciclastic sandstones, culminating with development of carbonate reefs in the uppermost stratigraphic level. Continued base-level fall led to deposition of soils on top of the carbonates. Thereafter, a deepening-upward trend suggests renewed extensional fault activity mainly on the NE-trending, southern fault segment, with a second extensional faulting climax indicated by a 500 m thick grain-stone to marly limestone succession. Limited siliciclastic input in this succession suggests the basin was detached from the sediment source represented by the nearby footwall basement (core complex), and that the aforementioned feeder-canyon was abandoned as a sediment point-source. Instead, debris from shallow marine carbonate production interfingered with small fans sourced from spatially limited footwall catchments. The marine to continental transition in the Bandar Jissah Basin highlights the delicate balance between sedimentary base-level and fault activity along basin bounding faults, which results in significant spatial and vertical facies contrasts.

9.1.2. Serck et al. (2019). Vinterkonferansen 2019, Bergen.

Serck, C.S.¹, Braathen, A.¹, Faleide, J.I.^{1,2}, Midtkandal, I.¹ and Kjølhamar, B.³ (2019). Multi-stage rifting, fault reactivation styles and growth basin architecture; evolution of the Terningen Fault Complex and Fingerdjupet Subbasin, southwestern Barents Sea.

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Accepted for oral presentation

Åknes rockslide hydrogeology

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Åknes rockslide, located in Storfjorden (Møre and Romsdal County), is one of the priority sites monitored by NVE since 1986. In 2004, an automated monitoring system was installed, collecting data until present-day. These include extensometer data, high accuracy GPS data, borehole data (groundwater levels and seismic data), and meteorological data (Grøneng et al., 2011).

In 2017, NVE decided to study in more detail the groundwater conditions in Åknes in order to assess the feasibility of a drainage operation that seeks to increase the rockslide stability. In this context, the University of Oslo is collaborating with NVE in order to (1) map, characterize and quantify groundwater recharge and discharge; (2) identify the main groundwater flow paths along the rockslide and adjacent upslope area; and (3) ultimately, develop a hydrogeological model of the Åknes rockslide.

From June to September 2018, extensive field campaigns were conducted in Åknes to assess the fracture network of the area upslope of the back-scarp, and to investigate groundwater chemistry and discharge rates along the whole mountain slope.

Preliminary results indicate that the area upslope of the back-scarp is moving. There, fracture networks follow the trend observed in the collapsing slope, as suggested by vertical drill holes, with interconnected exfoliation, slope-parallel fractures in schistose gneiss and steep fracture sets in quartz-feldspar gneiss. Steep fractures allow infiltration of surface water, recharging groundwater downwards to the unstable slope. There, the groundwater chemistry and discharge rates indicate higher residence times in the lower part of the slope, with ephemeral discharge at the higher and lower spring horizons, and perennial discharge at the middle spring horizon, which is located at the bottom of the fastest moving rock mass. Processing results of the entire dataset will be implemented in a rock-slope hydrogeological model that will be further quality assured by subsequent drilling of drainage holes.

Grøneng et al. (2011). Meteorological effects on seasonal displacements of the Åknes rockslide, western Norway. *Landslides*, 8:1-15

Hydrogeological tools in urban runoff management – case study from Torshovdalen, Oslo

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The Stormwater Management Strategy for Oslo, adopted in 2014, aims to reduce flooding risk and contributes to the achievement of a blue-green city where surface watercourses are an important component of the urban landscape. Daylighting of streams (also known as deculverting) entails re-directing urban runoff that was formerly transported in underground pipeline systems into the surface. In an urban setting, such actions demand a comprehensive understanding of the water cycle in the city, with surface water infiltration and groundwater discharge playing a crucial role on the quantity and quality of urban runoff water.

The planned opening of a new waterway in Torshovdalen has motivated an interdisciplinary study led by the Agency for Water and Sewerage in Oslo municipality. In this context, hydrogeological investigation tools are being implemented to assess the surface water infiltration capacity, water storage below the ground, groundwater discharge, and water quality in surface and groundwater bodies. For this purpose, field-campaigns were conducted since June 2018, and three groundwater observation wells were drilled.

Preliminary results indicate a relatively uneven fractured bedrock topography overlaid by loose materials made up of anthropogenic filling, sand and marine clays. Infiltration tests indicate a low infiltration capacity which is corroborated by the predominance of fine-grained materials (fine sand to clay), and the occurrence of groundwater seepage horizons. In terms of water quality, wide ranges of total dissolved solids, *E. coli* and coliform bacteria are observed in surface and groundwater, spanning from relatively pristine water to clearly contaminated water. The impact of clay-rich soils on the water cycle of the city is two-folded; on one hand surface water infiltration is hindered, while on the other hand, contaminants can be retained, contributing to the natural depuration of groundwater which, in turn, is likely to feed watercourses in downstream areas of the city.

Multi-stage rifting, fault reactivation styles and growth basin architecture; evolution of the Terningen Fault Complex and Fingerdjupet Sub-basin, southwestern Barents Sea

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Complexity in fault shape, fault displacement pattern and deformation of host rocks is inherent in any multi-

stage rift basin. Different styles of fault growth and reactivation during successive rift phases yield non-planar fault geometries that lead to folding of host rocks upon further fault displacement. Fault-related folding modifies accommodation development in rift basins with implications for the position and architecture of syn-rift sedimentary packages.

The Terningen Fault Complex represents the boundary between the Fingerdjupet Subbasin and the Ringsel Ridge. The evolution of the Terningen Fault Complex from the Carboniferous to Early Cretaceous has implications beyond the Fingerdjupet Subbasin, not only for the early evolution of the deep Bjørnøya Basin to the west but also late evolution of the eroded Bjarmeland Platform to the east. Different growth basin types are tied to the following key stages in the development of the Terningen Fault Complex: (1) Inferred Caledonian contractional tectonics followed by extensional collapse generating gently dipping detachment faults, (2) Carboniferous rifting with steep faults soling out in the aforementioned detachment faults, thus generating the listric geometry that establish the Fingerdjupet Subbasin as a semi-regional rollover basin, (3) Late Permian faulting in the overburden with subsequent dip linkage with Carboniferous faults (4) earliest Cretaceous faulting decoupled from Late Permian faults, resulting in deposition of fault-tip monocline growth packages and “ordinary” growth wedges related to surface faulting in planar faults (5) Aptian faulting with upward propagation of earliest Cretaceous faults. Dip linkage with Late Permian faults gave a ramp-flat-ramp fault geometry, fault-bend folding of Lower Cretaceous strata and deposition in a fault-bend fold synclinal basin. Finally, (6) fault shape adjustments with deactivation of ramp-flat-ramp structure lead to deposition of “ordinary” growth wedges and fault-tip monocline growth packages. Accordingly, repeated fault reactivation events controlled the formation, shape and infill of stacked growth basins.

Intermediate water in the Denmark Strait during Dansgaard-Oeschger Events

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Two sediment cores, one from the northern part of the Denmark Strait and the other from the Faroe-Shetland Rise, are used to investigate the regional expression of intermediate water variations in the Nordic Seas across Dansgaard-Oeschger (D-O) events and their relationship to sea ice growth and decay. We present benthic Mg/Ca temperature reconstructions together with stable isotope $\delta^{18}\text{O}$ from cores retrieved from 770 and 1500m water depth, identifying a recurring warming that takes place in unison across the Nordic Seas at intermediate depth during Greenland Stadials. The warm temperatures ($3^\circ \pm 1^\circ\text{C}$) are typical of slightly cooled Atlantic Water. To examine the physical capability of the Nordic Seas to retain warm temperatures at depth we implement an eddy-resolving configuration of the Massachusetts Institute of Technology General Circulation Model with idealized topography to test the effects sea ice has on ocean temperature distribution both horizontally and vertically. With the presence of sea ice, warm waters from the east are retained in the western Nordic Seas. An external freshwater input is needed for the warm temperatures to extend to depth (~1200 m). A balance between eddy heat fluxes and diffusion is responsible for the warm temperatures at depth.

Quantitative mapping of ravinement valleys in central Trøndelag using 4D geomodeling

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Changes in the landscape across Norway have for the past decade become more of a focal-point in trying to understand the impact of human activity over time, and how it has affected the landscape. Studying this has however been challenging since a true quantitative representation of the different landscape types, and how they change over time, has been lacking. It has therefore been difficult to the impact of human activity, especially the effect of alternations spanning the last four decades.

Current mapping tools, such as GIS and CAD systems can read, to some degree passively visualise maps in 3D, but neither of these systems have the capacity to integrate detailed understanding of the geology with surface related variations in a proactive manner depicting changes over time as a function of the physical process effecting the landscape.

This presentation aims to elucidate how a practical application of the understanding of geological processes and use of geomodelling software enables knowledge-driven rather than data-driven modelling. This, together with systematic analysis of detailed surface maps using azimuth and dip allows for the mapping of existing ravinement valleys generated within the marine clays that were deposited following the transgression at the time

9.2. Articles, co-author

9.2.1. Corseri et al. (2018)

A diverted submarine channel of Early Cretaceous age revealed by high-resolution seismic data, SW Barents Sea.

Corseri, R.¹, Faleide, T. S.^{1,2}, Faleide, J. I.^{2,3}, Midtkandal, I.², Serck, C. S.², Trulsvik, M.^{1,4}, & Planke, S.^{1,3}

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9.2.2. Midtkandal et al. (in press)

Lower Cretaceous Barents Sea strata: epicontinental basin configuration, timing, correlation, and depositional dynamics

Midtkandal, I.¹, Faleide, J. I.^{1,2}, Faleide, T. S.¹, Serck, C.S.¹, Planke, S.^{2,3}, Corseri, R.², & Nystuen, J.P.¹

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Accepted with revisions in *Geological Magazine*.

9.2.3. Anell et al. (in press)

Influence of structural highs on Triassic deposition on the northern Barents Shelf

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Accepted in Geological Society, London, Special Publications: Cross-Border Petroleum Geology and Exploration: The British and Norwegian Continental Margins

9.2.4. Faleide et al. (in press)

Early Cretaceous shelf platform delta lobes and faults in the Hoop area, southwestern Barents Sea – insight from high-resolution seismic data.

Faleide, T. S.¹, Midtkandal, I.¹, Planke, S.^{2,3}, Corseri, R.², , Faleide, J. I.^{1,3}, , Serck, C. S.¹, & Nystuen, J.P.¹

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9.3. MSc student co-supervision

9.3.1. Wibecke Knudtzon Kamp (2016)

Permian to Late Triassic structural and stratigraphic evolution of the Fingerdjupet Subbasin.

9.3.2. Julie Linnéa Sehested Gresseth (Spring 2019)

Deep structure of the Fingerdjupet Subbasin; influence of Caledonian structural grain on Late Paleozoic to Mesozoic rifting.