Tectonostratigraphic evolution of a multi-episodic rift

The northern Norway - Greenland rift: from post-orogenic exhumation to deep marine turbidites

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‘The world around us is consistent and non-judgmental.
It functions and leaves thinking to us.’

– B. Stevens

Hermannsdalstinden, Moskenesøy, Lofoten

Preface to the thesis

This dissertation for the degree of philosophiae doctor (PhD) has been submitted to the Department of Earth Science at the University of Bergen. This project was initiated by the University of Bergen in cooperation with Norske Shell. Funding and access to data is provided by Norske Shell. Cooperation with the WOLLGAN project (a former co-operative research project involving Statoil, Saga, Amoco, the Norwegian Petroleum Directorate and the Geological Institute of the University of Copenhagen) was established in 2014 in order to expand access to field data from East Greenland.

The candidate enrolled in the PhD programme at the Department of Earth Science at the University of Bergen while carrying out the research between May 2012 and May 2015. The research was supervised by Professor Atle Rotevatn (University of Bergen) and co-supervised by Professor Robert Gawthorpe (University of Bergen), Professor William Helland-Hansen (University of Bergen) and Dr. Rodmar Ravnås (Norske Shell).

This dissertation is divided in to three parts. An introduction to the various topics of this project is provided in the first part. Here the aims and objectives are outlined and a brief description of methods is given. Part two contains the results of this study, presented in four scientific papers that together make up the main body of the thesis. The findings of these studies are summarised in part three in an attempt to synthesise the results of the project.

The scientific papers have been published in, or are being prepared for submission to, different relevant journals. The template of references to literature and figures therefore varies between the different papers. References cited in the introduction and synthesis are listed at the end of the dissertation.

Contents

Acknowledgements

First and foremost I wish to express my gratitude to my supervisors: Rob Gawthorpe, William Helland-Hansen, Rodmar Ravnås and especially Atle Rotevatn for setting up the project, arranging cooperation with other institutions along the way and basically teaching me how to write a scientific paper. It has been an inspiring and instructive journey. I would like to thank the people at the exploration department of Shells Stavanger offices for the motivational and intellectual support during my visits. Sten-Andreas Grundvåg, Ivar Midtkandal, Thomas Berg Kristensen and Anna Ksienzyk are thanked for pleasant cooperation during the field-based components of my research. Arild Andresen is acknowledged for invaluable help and material support in setting up our Greenland expedition.

I wish to thank Christian Eide for three years of virtually uninterrupted dialogue on geology (and a shortlist of other topics), ranging from discussions on the origin of the Norwegian mountains to deadlocked arguments about strike/dip notations, taking place usually at lunch but occasionally in the unlikeliest of places such as Constable Pynt or Hardangerjokullen. It has been most entertaining and our comradery has encouraged me along the way. I feel deeply indebted also to my friend Jord de Boer for inspiration and regalement. The unique mixture of professional enthusiasm and absurd humour that our friendship provides, which somehow always seems to come out in its most extreme form during fieldwork such as in Sinai and Lofoten in recent years, has cheered me up throughout the course of the project. Peter Bormann, Jos van de Vrande and Tore Aadland are thanked for insight and reflection; your intelligent, sometimes skeptical but always well-informed commentary made me reconsider my approach on more than one occasion. A word of acknowledgment goes out also to my friends Eric van Zandwijk and Willem van der Bilt, whose fields of expertise (water management, quaternary geology) only overlap with my own on their mutual fringes; yet the adventurous nature and original thinking that you both champion has formed an inspiration, and undoubtedly influenced the coming about of this thesis.

I wish to address a special word of recognition to my dearest Amalie for the love, companionship and support she has given me since we first met, when I was halfway my doctoral studies here in Bergen. I feel blessed, too, by the warm welcome I received into the Solberg family. Finally, I express my deep gratitude to my family in the Netherlands; Wouter, Teunie and especially my parents Chris and Irene, for their unconditional love and excellent parenting throughout my youth and early adulthood. If it was not for their encouragement and guidance during the countless, nondescript days spent at high school I would almost certainly have missed the opportunity to attend higher education. I am inexpressibly grateful for making me hold on then, and now dedicate this thesis to the both of you.

Gijs Allard Henstra
Bergen, May 9th, 2015

Abstract

The aim of this project is to improve the tectonostratigraphic understanding of the northern part of the Norwegian passive continental margin, the so-called Lofoten margin, and contribute to the wider understanding of normal fault evolution and depositional style in multiphase rift systems. Several key aspects of the evolution of the Lofoten margin have been documented and analysed using a dense database of new as well as re-processed 2-D and 3-D seismic reflection surveys:

i) the nature of Palaeozoic extension in relation to post-orogenic exhumation;
ii) the structural evolution of the Lofoten margin across the various rift episodes of the Mesozoic;
iii) the evolving depositional environment and sedimentary systems of the North Træna Basin.

In addition, sedimentological fieldwork was carried out on the conjugate margin in East Greenland, in order to provide an outcrop analogue for deep marine rift climax deposits.

Large scale, extensional geometries are observed on seismic below the Base Mesozoic horizon in the North Træna Basin. In conjunction with earlier studies of exhumation in the Lofoten area, which point at a relative young age for the exhumation of deep crustal levels and describe the Lofoten Ridge as a Permian-age metamorphic core complex, these geometries are interpreted to represent the break-away zone of a Cordilleran-style metamorphic core complex. The mechanisms behind the protracted exhumation of the Lofoten basement are discussed.

The hanging wall depocentres of the Vesterdjupet Fault Zone have been mapped in detail using seismic data. A reconstruction of the structural framework per rift episode is presented. It is described how faults that had formed during the Early Triassic rift episode became selectively reactivated and linked during Late Jurassic rifting, which allowed the establishment of a single, through-going fault zone during renewed rifting towards the middle Cretaceous. Different models that could explain

this fault zones characteristic zigzag plan-view geometry are discussed within the context of multiphase rifting.

A seismic record of the sedimentary fill of the North Træna Basin, which forms the hanging wall to the Vesterdjupet Fault Zone, is investigated. It is demonstrated how the style of basin-fill tends to follow regional developments, but occasionally becomes strongly influenced by the progressive, stepwise establishment of the boundary fault zone over several rift episodes. These rift episodes are separated in time by long inter-rift periods, during which inactive faults become buried and the rift topography is replaced by a shelf break margin. Later rift episodes are dominated by instantaneous strain localisation, resulting in pronounced fault block rotation, which affects the routing of sedimentary systems and dictates abrupt changes in the relations among sediment supply, sea-level and subsidence.

The results from the outcrop analogue study show that the majority of coarse clastic sediments of the syn-rift Wollaston Forland Group represent a continuum of deposits from a single type of gravity flow. Such gravity flows were sourced from the crystalline footwall and deposited in a wedge in the hanging wall. Several types of flow transformation that these gravity flows undergo during transport are identified and discussed. The observed fault-parallel facies variability is explained as a consequence of structural control on sediment routing from the footwall source area to the hanging wall.

In the synthesis presented at the end of this thesis the results of the different papers are integrated and discussed, thus highlighting the specific aspects of a rift basin that is formed by multiple rift episodes separated by long (> 20 Myr) inter-rift periods.

Uittreksel

Deze dissertatie is gericht op het bevorderen van het tektonostragrafische begrip in het meest noordelijke segment van de Noorse passieve continentale marge, de zogenaamde Lofoten marge, en draagt zodoende bij aan een beter begrip van de ontwikkeling van de afschuivingsbreuken en het afzettingsmilieu in meerfasige slenksystemen. Aan de hand van nieuwe en bewerkte 2D en 3D seismische reflectie datasets zijn de volgende hoofdaspecten van de ontwikkeling van de Lofoten marge aan een nadere analyse onderworpen:

i) de aard van Paleozoïsche extensie in relatie tot post-orogene opheffing van de diepere korst;
ii) de structurele ontwikkeling van de Lofoten marge gedurende de verschillende fases van slenkvorming in het Mesozoïcum;
iii) het veranderende afzettingsmilieu van het Noord Træna Bekken.

Aanvullend is veldwerk uitgevoerd op de conjugate marge in Oost Groenland, voor een vergelijking met de diep mariene, slenk-gerelateerde afzettingen in Lofoten.

Grootschalige afschuivingsgeometrieën die zijn waargenomen op seismische data onder Mesozoïsche strata in het Noord Træna Bekken. In samenhang met eerdere studies naar de opheffing in Lofoten en omstreken, waarin de relatief late opheffing en het aan de oppervlakte komen van de diepere korst reeds is aangetoond , en waarin de Lofoten Rug is beschreven als een metamorfisch kern-complex uit het Perm, kunnen deze geometrieën worden verklaard als de uitbreekzone van een Cordilerra-achtig metamorf kern-complex. Tegen deze achtergrond worden de onderliggende mechanismes van de langdurige opheffing van het Lofoten sokkel nader toegelicht.

De ontwikkeling van de Vesterdjupet Breukzone gedurende het Mesozoïkum is bestudeerd door de verschillende sub-bekkens in de hangende wand van deze breuk in kaart te brengen. Beschreven wordt hoe breuken, eerst gevormd in het Vroeg-Trias, selectief werden gereactiveerd en verbonden tijdens de slenkvormings-fase van het Laat-Jura, hetgeen op zijn beurt het ontstaan van een enkele, doorgaande

breukzone tijdens het Krijt mogelijk maakte. Verschillende modellen die het karaketeristieke zigzag-patroon van deze breukzone kunnen verklaren, worden bediscussieerd in verband met meerfasige slenkvorming.

De sedimentaire invulling van de hangende wand van de Vesterdjupet Breukzone is bestudeerd aan de hand van seismische data. Er wordt aangetoond dat de bekkenvulling de neiging heeft algemene, regionale ontwikkelingen te volgen, maar daar af en toe van afwijkt als gevolg van de progressieve, stapsgewijze breuk-gerelateerde vorming van het bekken tijdens de verschillende slenkvormings-fases. Deze fases werden afgewisseld met langdurige tussen-rift periodes, waarin de niet langer actieve breuken werden toegedekt en de horst- en slenk topografie plaats maakte voor een continentaal plat. De late slenkvormings-fases werden gekenmerkt door de directe focus van verplaatsing langs de hoofdbreuken, hetgeen tot uiting komt in de versterkte rotatie van de breukblokken. Deze breukblok-bewegingen zijn op hun beurt van invloed op de loop van sedimentaire systemen en onderlinge relaties tussen sedimenttoevoer, zeespiegel en bodemdaling.

De resultaten van het veldwerk wijzen uit dat de overgrote meerderheid van de grove sedimenten van de Wollaston Forland Groep een continuüm aan afzettingen voorstelt, alle afkomstig van een enkel slag sediment-zwaartekrachtstroming. Zulke stromingen werden gevoed door erosie van de kristallijne voetwand en afgezet in de onderwaterstaande, aanliggende hangende wand. Verscheidene stroomtransformaties die deze stromingen ondergingen, zijn geïdentificeerd en worden vervolgens bediscussieerd. Verder wordt de waargenomen breuk-parellele variabiliteit in faciës verklaard in verband met de constatering dat de aanvoer van sediment van de voetwand naar de hangende wand in grote mate werd bepaald door het breuksysteem.

In de synthese aan het eind van deze dissertatie worden de resultaten van de vier artikelen met elkaar in verband gebracht en bediscussieerd, daarbij wordt in het bijzonder ingegaan op de specifieke eigenschappen van een slenk die gevormd is in een proces waarbij verschillende rift-periodes worden afgewisseld door lange (> 20 miljoen jaar) tussen-rift periodes.

Sammendrag

Målet med dette prosjektet er å forbedre den tektonostratigrafiske forståelsen av den nordlige delen av den norske passive kontinentalmarginen, den såkalte Lofotenmarginen, og bidra til en bredere forståelse av utvikling av normalforkastninger og avsetningsmiljø i flerfase riftsystemer. Flere sentrale aspekter ved utviklingen av Lofotenmarginen er dokumentert og analysert ved hjelp av en tett database med ny så vel som reprosessert 2-D og 3-D seismikk:

i) arten av palaeozoisk ekstensjon i forhold til post-orogonetisk heving av jordskorpen;
ii) den strukturelle utviklingen av Lofotenmarginen på tvers av de ulike riftepisoder i mesozoikum;
iii) utvikling avsetningsmiljø og sedimentære systemer av Nord Træna-bassenget.

I tillegg ble sedimentologisk feltarbeid utført på Øst-Grønland, på Lofotens konjugatmargin, for å gi en analog for de dypmarine avsetningene under riftklimaks.

Storskala ekstensjonsgeometrier er observert på seismikk under bunn-mesozoikum-horisonten i Nord Træna-bassenget. I forbindelse med tidligere studier av landheving i Lofoten, som peker på en relativ ung alder for heving av nedre jordskorpe, og beskriver Lofotenryggen som et metamorfe kjernekompleks av permisk alder, er disse geometriene tolket til å representere break-away-sonen i et Cordilleran-type metamorft kjernekompleks. Mekanismene bak den langvarige heving av Lofotens grunnfjell blir diskutert.

Bassengene i den hengblokken av Vesterdjupet Forkastningssone har blitt kartlagt i detalj ved hjelp av seismiske data. En rekonstruksjon av det strukturelle rammeverket per rift episode presenteres. Det beskrives hvordan forkastninger dannet under den tidlig-triasiske rift episoden ble selektivt reaktivert og knyttes sammen under rifting i sen jura, som tillot etablering av et enkelt, gjennomgående forkastningssone under fornyet rifting mot midten kritt. Ulike modeller som kan forklare denne

forkastningssonens karakteristiske sikksakk-geometri i kartplanet er diskutert innenfor rammen av flerfase rifting.

En seismisk registrering av sedimentær innfylling av Nord Træna-bassenget, som danner hengblokken til Vesterdjupet Forkastningssone, er undersøkt. Det er demonstrert hvordan stilen til bassenginnfyllingen har en tendens til å følge den regionale utviklingen, men tidvis blir sterkt påvirket av den trinnvis etablering av en grenseforkastningssone over flere rift episoder. Disse riftepisodene er adskilt i tid med lange inter-rift perioder, hvor inaktive forkastninger blir begravd og rift-topografi er erstattet av en margin med tydelig sokkel og eggakant. Senere rift episoder er dominert av momentan belastningslokalisering, noe som resulterer i rotasjon av forkstningsblokker, noe som påvirker ruting av sedimentære systemer og dikterer endringer i forholdene mellom sedimentforsyning, havnivå og innsynkning.

Resultatene fra analogstudien viser at flertallet av grove klastiske sedimenter av syn-rift Wollaston Forland Gruppen representerer et kontinuum av innskudd fra en enkelt type gravitasjonsstrøm. Slike gravitasjonsstrømmer hadde sin kilde i en krystallinsk liggblokk og avsatt i en kile på hengblokken. Flere typer flyttransformasjon disse gravitasjonsstrømmene gjennomgår under transport er identifisert og diskutert. Den observerte forkastningsparallele faciesvariabilitet er forklart som en konsekvens av strukturell kontroll av sedimentføring fra kildeområdet i liggbloken til den avsetningsområdet i hengblokken.

I syntesen på slutten av denne avhandlingen blir resultatene av de ulike artiklene integrert og diskutert, og fremhever dermed bestemte aspekter av et riftbassenge som er dannet av flere riftepisoder atskilt med lange (> 20 million år) inter-rift perioder.

Introduction

Passive margins

The process of continental rifting forms an integral part of the plate tectonic cycle and rifted margins form important targets for exploration of hydrocarbons (Fraser et al., 2007). Accordingly, passive margin evolution has been studied extensively and a wide range of styles is recognized; their classification has traditionally been based on (i) geometry (rifted, sheared or transtensional; Fowler, 1990), (ii) the nature of the transitional attenuated crust (volcanic versus non-volcanic; White and McKenzie, 1989) or (iii) sedimentation history (sediment-starved versus nourished; Milliman and Meade, 1983). Such classifications are descriptive and do not touch upon the underlying mechanism of continental rifting.

It was shown that the uniform stretching model of McKenzie (1978) cannot account for all observed features of certain passive continental margins, such as the exposure of stretches of serpentinised continental mantle (Davis & Kusznir, 2002). Such margins are better understood as a result of depth-dependent stretching and two-stage breakup, which requires a certain degree of decoupling between crust and mantle lithosphere. In recent years, a new approach to the classification of passive margins has emerged that looks at the mechanical and thermal processes that lay at the base of continental breakup (Huismans & Beaumont, 2007). This classification states that various properties of rifted margins (e.g. magmatism, structural style and sedimentation history) can be predicted by knowing the rheological properties of the original, pre-rift lithosphere which dictates style of depth-dependent stretching (Huismans & Beaumont, 2011).

Fault evolution in multiphase rift systems

Results from the numerical models of Brune (2014) indicate that rifting prefers oblique reactivation of mechanically weak zones at an angle to far-field stresses. During initial rifting, en-echelon fault arrays develop over these weak zones. The

locus of extension may migrate laterally with time as rifting progresses (Brune, 2014; Naliboff & Buiter, 2015).

Continental breakup typically involves multiple phases of lithospheric extension, i.e. multiphase rift systems. In this dissertation we distinguish between episodes, phases and events following the definition of Ravnås et al. (2000). In practice, the term 'multiphase rift' is used for any rift basin formed by multiple extension events, regardless of timespan.

Single rift episodes are typically characterised by rift initiation, followed by fault interaction and linkage and finally rift climax (Gupta et al., 1999; McLeod et al., 2000). In multiphase rift systems which involve more than one rift episode, these subsequent stages are repeated, meaning that periods of rift climax are followed by renewed fault initiation, often separated by a period of tectonic quiescence (Ravnås et al., 2000; Bell et al., 2014). Subsequent rift episodes may utilise and reactivate pre-rift structures (Clifton et al., 2000; Morley et al., 2004; Paton, 2006). In a multiphase rift system, normal faults that form during the early rift episode(s) influence the structural style of subsequent rift episodes as is shown by using physical analogue models (Keep & McClay, 1997; Henza et al., 2011).

Traditionally the evolution of faults is described as the progressive incidental coalescence of initially isolated growing fault segments. This process has been documented in nature (e.g. Peacock and Sanderson, 1991; Cartwright et al., 1996; McLeod et al., 2000) and is recreated in modelling studies (e.g. Scholz et al., 1993; Crider and Pollard, 1998, Cowie et al., 2000). Heterogeneities in the (crystalline) bedrock or pre-existing structures are known to influence normal fault growth, by providing a kinematic relationship between fault segments since their inception (Morley et al., 1999). In such a case the fault initiation phase is not characterised by the distribution of displacement over numerous isolated faults (e.g. Cowie et al., 2000) but represents the establishment of a single structure from the outset (the coherent fault model; Walsh et al., 2002, 2003). Reactivation of a normal fault in a multiphase rift system is documented in nature by Giba et al. (2012) and Jackson &

Rotevatn (2013) who demonstrated that the process of reactivation may follow the coherent fault model, starting with the inception of a series of kinematically linked faults along the length of the reactivated, buried fault (Walsh et al., 2002). It was pointed out by Bell et al. (2014) that existing generic evolution models address single episode rift systems (Cowie et al., 2000), and that such models do not yet exist for rift systems with multiple episodes, i.e. extensional basins formed by repeated cycles of rift initiation and climax.

Sedimentary fill of rift basins

Rift basins can accommodate a wide range of depositional environments, from sub-aerial alluvial fans, rivers and deltas to deep water (hemi-) pelagics. Modern-day rift basins in a terrestrial setting are by default readily accessible for studying the more proximal end of this depositional spectrum (e.g. the Rio Grande rift; Brister and Gries, 1994; Leeder et al., 1996). The same holds for marginally marine environments in submerged rift basins (e.g. the fan deltas of the Gulf of Corinth: Collier and Dart, 1991; Rohais et al., 2007). Depositional processes in modern deep water rift basins have been studied in Lake Baikal (Colman et al., 2003), Gulf of Corinth (Lykousis et al., 2007) and the east Africa Rift (Lyons et al., 2011). Generic models for sedimentation in an active extensional basin have been put forward for a single cycle of rift initiation to rift climax (Gawthorpe & Leeder, 2000; Ravnås and Steel, 1998; Withjack et al., 2002; Gawthorpe and Leeder, 2000).

Submerged rift basins are to a large degree hidden from direct observation; it requires significant uplift and erosion for them to be exposed, while they form typically when plate motions are divergent. This explains (partly) why outcrop examples of deep marine rift climax deposits are rare; they are known from Wollaston Forland (East Greenland; Surlyk, 1978), the Inner Morray Firth (UK; Wignall & Pickering, 1993) and the Gulf of Corinth (Greece; Gobo et al., 2014). These outcrops are dominated by subaqueous gravity flow deposits.

Recent research in the field of subaquous gravity flows focussed on turbulence damping and variability of hydraulic regime within single events (Postma et al., 2009;

Talling et al., 2007). Gravity flows released into a narrow basin may be forced to decelerate over confining slopes (Mutti et al., 1999; Patacci et al 2014). Such turbulence damping likely also takes place in gravity flows released into deep water rift basins, which often exhibit a confined physiography, but is rarely documented.

The Northern Norway-Greenland rift

The Norwegian passive continental margin forms part of the eastern side of the greater Atlantic continental rift system which is associated with the break-up of the supercontinent Pangea. (Doré, 1992). It consists of three c. 400 km long segments; the Lofoten-Vesterælen margin forms the northernmost segment and is bordered by two crustal scale lineaments. The Bivrost fault zone in the southwest separates it from the greater Vøring Basin and Trondelag platform; to the northeast the margin segment is bordered by the Senja fault zone that forms an integral part of the western Barentsz Sea transform margin. The Norwegian passive continental margin resembles a volcanic rifted margin. However, compared to the Vøring margin to the south, the Lofoten-Vesterålen margin is characterised by reduced magmatism (both intrusive and extrusive; Berndt et al., 2001; Tsikalas et al., 2001) and underplating is less well-developed (Mjelde et al., 1993). Moreover, the Lofoten-Vesterålen crust experienced relatively moderate extension during rifting (Tsikalas et al., 2012). Break-up style is consistent with depth-dependent stretching of the lithosphere during (early) sea floor spreading (Kusznir et al., 2004; Tsikalas et al., 2008).

The Norwegian passive continental margin is a multiphase rift system characterized by major extensional episodes during the Permo-Triassic and Middle-Late Jurassic (Doré et al., 1999; Færseth, 2012). Along the Lofoten-Vesterålen segment at the northern end of the margin, extension continued into the Early and Late Cretaceous (Hansen et al., 1992; Løseth and Tveten, 1996; Tsikalas et al., 2001; Hansen et al., 2012). This margin segment is characterized by more or less continuous subsidence throughout the Mesozoic (Faleide et al., 2008). Normal faults and their hanging wall depocentres formed during the successive rift episodes have, for the most part, been buried and preserved. The relatively under-explored Lofoten-Vesterålen margin

forms an ideal natural laboratory for studying multi-episodic rifting, because Cretaceous reactivation of both Permo-Triassic and Late Jurassic structural elements can be demonstrated.

The link between fault patterns mapped both offshore and onshore has been investigated by different workers (Wilson et al., 2006; Bergh et al., 2007; Hansen et al., 2012). Along the Lofoten-Vesterålen margin, polarity and geometry of faults vary within and between sub basins; as a result, several distinct fault populations are recognized. The spatiotemporal development and interaction of these fault populations has been subject of debate in recent years. It has been argued that the different fault populations that are being recognized reflect distinct rift pulses following a rotation of the regional extensional stresses with time (Bergh et al., 2007), whereas Wilson et al. (2006) suggest that they formed simultaneously as conjugate sets under a uniform stress field, locally perturbed as a result of an inherited Caledonian basement grain.

While the structural evolution of the area of interest has received much attention in recent years, the basin-fill component has received considerably less attention (Smelror et al., 2001). Constraints on the structural framework based on sedimentary fill (and vice versa) are sometimes mentioned in literature (e.g. Bergh et al., 2007), but a dedicated study linking depositional trends to the tectonic evolution of the Lofoten-Vesterålen margin has not been carried out hitherto.

Aims and objectives

The overall aim of this dissertation is to contribute to the understanding of the evolution of normal faults and depositional style in multiphase rift systems, by investigating the tectonostratigraphic evolution of the northern Norwegian-Greenland rift.

The first objective is to reconstruct the earliest extensional history of the Lofoten margin following the collapse of the Caledonian orogeny. This is achieved by

studying seismic reflection data on which the pre-Mesozoic basin configuration of the Lofoten margin is imaged. The result of this work is presented in paper 1.

The second objective is a reconstruction of the evolution of the Vesterdjupet Fault Zone, one of the major normal fault zones that characterise the Lofoten margin. By mapping and characterizing various seismo-stratigraphic intervals in is hanging wall, it is demonstrated how this fault zone formed during three rift episodes by repeated reactivation and linkage of earlier faults. This case study for the evolution of a major segmented normal fault during multiphase rifting is presented and discussed in paper 2.

The third objective is to reconstruct depositional environments in time and space for the North Træna Basin, the hanging wall of the Vesterdjupet Fault Zone. The stratigraphic geometries observed on seismic data are interpreted and compared to regional depositional trends, as well as the evolution of the Vesterdjupet Fault Zone documented in paper 2. This case study of the evolution of sedimentary fill of a rift basin that is characterised by multiple extension episodes is presented in paper 3.

The fourth objective is a sedimentological investigation of sediment deposited during the Late Jurassic to Early Cretaceous rift climax in East Greenland. In this study the different sedimentary systems that supplied clastic material to the basin are identified and the role of structural control on sediment routing is discussed. Furthermore, the deposits are described and analysed in order to determine the processes that formed them. The results of this outcrop study are presented in paper 4.

The fifth objective is to synthesise the results of the different papers in order to extract and discuss the main learnings and contribution to the understanding of extensional basins formed by multiple rift episodes.

Authorship statement and list of publications

The four papers that together make up the body of this thesis were produced in collaboration with the authors listed for each paper. Preparation, editing and submission of the papers were overseen primarily by the candidate. Responsibility for any errors in the coming about of the results as well as any erroneous interpretations or conclusions thus rests with the candidate. The contribution of the different authors is broken down and presented here:

Paper 1: Nature of Palaeozoic extension in Lofoten, north Norwegian Continental Shelf: insights from 3-D seismic analysis of a Cordilleran-style metamorphic core complex.
Published in Terra Nova 26, 247-252 (June 2014).
Henstra, G. A. & Rotevatn, A.

The candidate was responsible for seismic observations, drafting of figures and writing/editing the manuscript. A. Rotevatn contributed with important discussion and co-writing the manuscript.

Paper 2: Evolution of a major segmented normal fault during multiphase rifting: The origin of plan-view zigzag geometry.
Published in Journal of Structural Geology 74, 45-63 (May 2015)
Henstra, G. A., Rotevatn, A., Gawthorpe, R. L., Ravnås, R.

The candidate was responsible for seismic interpretation, drafting of figures and writing/editing the manuscript. A. Rotevatn, R. L. Gawthorpe and R. Ravnås contributed with important discussion and reviewed the manuscript.

Paper 3: Sedimentary systems in a submerged, episodically active rift basin: a seismic case study from the Lofoten Margin, North Norway
Manuscript (prepared for submission to Basin Research)
Henstra, G. A., Gawthorpe, R. L., Helland-Hansen, W., Ravnås, R., Rotevatn, A.

The candidate was responsible for seismic interpretation, drafting of figures and writing/editing the manuscript. R. L. Gawthorpe, W. Helland-Hansen, R. Ravnås and A. Rotevatn contributed with important discussion and reviewed the manuscript.

Paper 4: Sediment supply and depositional processes in a submerged half graben during rift climax, with special reference to transformation of submarine gravity flows: an outcrop study from East Greenland.

Manuscript (prepared for submission to Journal of Sedimentary Research)

Henstra, G. A., Grundvåg, S-A., Johannessen, E. P., Kristensen, T. B., Midtkandal, I., Nystuen, J. P., Ravnås, R., Rotevatn, A., Surlyk, F., Sæther, T., Windelstad, J.

This paper is the product of a combination of field data collected during different field seasons, in 1994 and 2014. The 1994 expedition, in which the candidate played no role, involved E. P. Johannessen, J-P. Nystuen, F. Surlyk, T. Sæther and J. Windelstad. Cooperation was initiated by A. Rotevatn after which the 2014 expedition was planned and prepared by the candidate and A. Rotevatn, and was carried out by the candidate along with S-A. Grundvåg, T. B. Kristensen, I. Midtkandal and A. Rotevatn. All expedition members contributed to the collection of the sedimentary logs. The candidate was responsible for interpretation of combined log data, drafting of figures (except Figure 13) and writing/editing the manuscript. S-A. Grundvåg, E.P. Johannessen, T.B. Kristensen, I. Midtkandal, J. P. Nystuen and A. Rotevatn contributed with important discussion and reviewed the manuscript.

5. Synthesis

5.1 Summary: multi-episodic rifting of the Lofoten margin

Palaeozoic extension and exhumation

In Lofoten, unroofing of Caledonian allochthonous sequences and the exhumation of lower crustal rocks occurred relatively slow in comparison to southern Norway, and lasted well into the Permian (Hames & Andresen 1996). In **paper 1** we document and discuss Palaeozoic, probably Permian, extensional features seen on seismic data in the offshore domain and propose a mechanism behind this long-lived exhumation history. We demonstrate how crustal extension and exhumation in Palaeozoic times was facilitated by a Cordilleran-style metamorphic core complex in the Lofoten area. This large asymmetric structure is dominated by a metamorphic dome consisting of lower crustal rocks, which consist of the partly submerged Lofoten Ridge and likely extends underneath the southern Ribban Basin. To the west we recognise a supra-detachment basin, or breakaway zone, of Palaeozoic age at the base of the North Træna Basin (**paper 1**).

The Early Triassic rift episode

During Late Permian - Early Triassic times, rifting focussed on the western edge of the Baltic shield, in the northern North Sea, Norwegian Sea and western Barents Sea (Doré, 1992; Brekke, 2000). In the Lofoten margin, this rift episode was characterised by the development of a series of parallel NNE-SSW-striking which formed primarily over the underlying Palaeozoic supra-detachment basin (**papers 1 and 2**). Where drilled, the Lower Triassic consists of fine- to very coarse-grained sediments derived from the local basement and deposited as alluvial fans under arid conditions (Hansen et al. 1992). The Triassic faults that form the precursors to the Vesterdjupet Fault Zone are interpreted to have formed as isolated features (**paper 2**).

The Middle Triassic to Middle Jurassic inter-rift period

A reduction in tectonic activity is placed at the transition from the Early to the Middle Triassic (Færseth, 2012) and extensional tectonics was not resumed before Late

Jurassic times (**paper 2**). Much of the area was uplifted at the transition between the Triassic and Jurassic periods (Hansen et al., 2012). The uplifted terrain was subsequently peneplained and transgressed in Middle Jurassic times. The southern Ribban Basin had remained a platform throughout this period (**papers 1, 2 and 3**; Hansen et al., 1992). This inter-rift period lasted c. 85 Myr and is characterised by deposition of fine- to medium-grained coastal plain to shallow marine sediments in the North Træna Basin (Hansen et al., 1992).

The Late Jurassic to earliest Cretaceous rift episode

Renewed rifting on the Lofoten margin initiated in the Late Jurassic. **Paper 2** demonstrates how Triassic faults were selectively reactivated and linked up to form zigzag-style fault zones. Open marine conditions prevailed across the down-faulted areas of the Lofoten margin. Depocentres that formed at some distance from (structural) highs remained sediment-starved, whereas those depocentres that were located adjacent to sediment source areas contain syn-tectonic, clastic wedges (**papers 3 and 4**).

The Early Cretaceous inter-rift period

The Base Cretaceous unconformity formed as tectonic activity decreased, and the overlying Valanginian to lower Albian interval represents another, c. 35 Myr long inter-rift period. During which the inherited Late Jurassic depocentres were effectively filled in (**papers 2 and 3**). The early part of this period is characterised by slow sedimentation in a distal setting whereas regressive clastic wedges developed during the Aptian and early Albian, similar to progradational pulses of shelfal sands elsewhere along the fringes of the northern North Atlantic rift (**paper 3**; Larsen et al., 1999).

The middle Cretaceous rift episode

The major fault zones of the Lofoten Margin were reactivated in the late Albian (**paper 2**). An up to two kilometre thick succession of fine-grained, marine sediments of late Albian age was deposited in the northern North Træna Basin and the Ribban Basin (**papers 2 and 3**). We describe clastic sedimentary systems in the immediate

hanging wall of the Vesterdjupet Fault Zone that were either axially sourced or derived from the exposed footwall; this depositional setting is compared to a similar setting seen in Lake Baikal and to the coarse grained gravity flows described in (**papers 3 and 4**). Middle Cretaceous faulting is also observed in the outer Vøring margin and the Faroe-Shetland Basin at this time (Brekke, 2000; Faleide et al., 2008; Larsen et al., 2010) whereas rifting had ceased in the North Sea and Møre-Trøndelag shelf. This indicates that the locus of extension had shifted closer to the central axis of the northern North Atlantic rift.

The early Late Cretaceous inter-rift period

The Cenomanian to Campanian represents a c. 20 Myr inter-rift period between Late Albian and Campanian rifting, and is characterised by uplift of the Utrøst Ridge, causing the NNE-SSW-trending basins of the Lofoten margin to become tilted to the south. Sedimentation rates peaked in the Vøring and Møre margin segments, whereas the Lofoten margin had become strongly divided by Albian fault block rotation, causing the outboard basins such as the North Træna Basin to be cut off from sediment sources in the east (**paper 3**).

The Late Cretaceous – Palaeogene rift episode

Normal faulting was resumed during the Campanian; reactivation of the Vesterdjupet Fault Zone was relatively mild (**paper 2**), while most strain was accommodated west of the Utrøst Ridge, close to the area of continental separation that took place towards the end of this rift episode (Tsikalas et al., 2001). Uplift of the Utrøst ridge and tilting of the North Træna and Ribban Basins reinvigorated, resulting in subaerial exposure and erosion of the northern parts of these basins whereas the southern parts were characterised by southward-directed turbidite systems that continued into the Træna Basin (**paper 3**; Vergara et al., 2001). This rift episode culminated in continental break-up in the Eocene (Mosar et al., 2002).

5.2 Tectonostratigraphic model for rift basins of the northern Norwegian-Greenland rift

A conceptual model for the evolution of rift basins that form during two distinct rift episodes, separated by an inter-rift period lasting several 10's of millions of years, is shown in Figure 1. This model is based (partly) on the Middle Jurassic to middle Cretaceous tectonostratigraphic evolution of the Lofoten margin and Wollaston Forland. Key aspects of this model include:

- The first rift episode contains an initiation phase (Fig. 1B), followed by a linkage phase during which individual faults begin to link up and form through-going fault systems. As displacement is facilitated by fewer faults, the depocentres that border these faults are subject to higher subsidence rates and may become under-filled (Fig. 1C; **paper 2**). Variability in depositional style is largely a function of proximity to hinterland sediment source areas. In figure 1C, the half-graben on the right hand side resembles the Ribban Basin and the Wollaston Forland Basin (**papers 3 and 4**) that border the hinterland, whereas the half-graben to the left, being disconnected from the hinterland, resembles the North Træna Basin during the Late Cretaceous (**papers 2 and 3**).
- When fault activity ceases, the inherited submerged rift terrain becomes filled up by a regression of inter-basinal, deltaic sedimentary systems (Fig. 1D). If sedimentation supply is sufficient, footwall highs are buried and a shelf break margin may develop **(paper 3**).
- During the second rift episode, strain is accommodated instantaneous by reactivation of only a select few through-going fault zones resulting in rift climax without preceding rift initiation or linkage stages (Fig. 1E). Pronounced subsidence and fault block rotation produces deep basins and reversals of sedimentary systems **(paper 3**).
- Following the subdivision of the area into elongated, deep basins, sedimentary fill of the post-rift period and that of possible subsequent rift events, is likely to be

composed almost exclusively of axially-sourced turbidite systems (Fig. 1F; **(papers 3 and 4**), followed by the establishment of a shelf break margin.

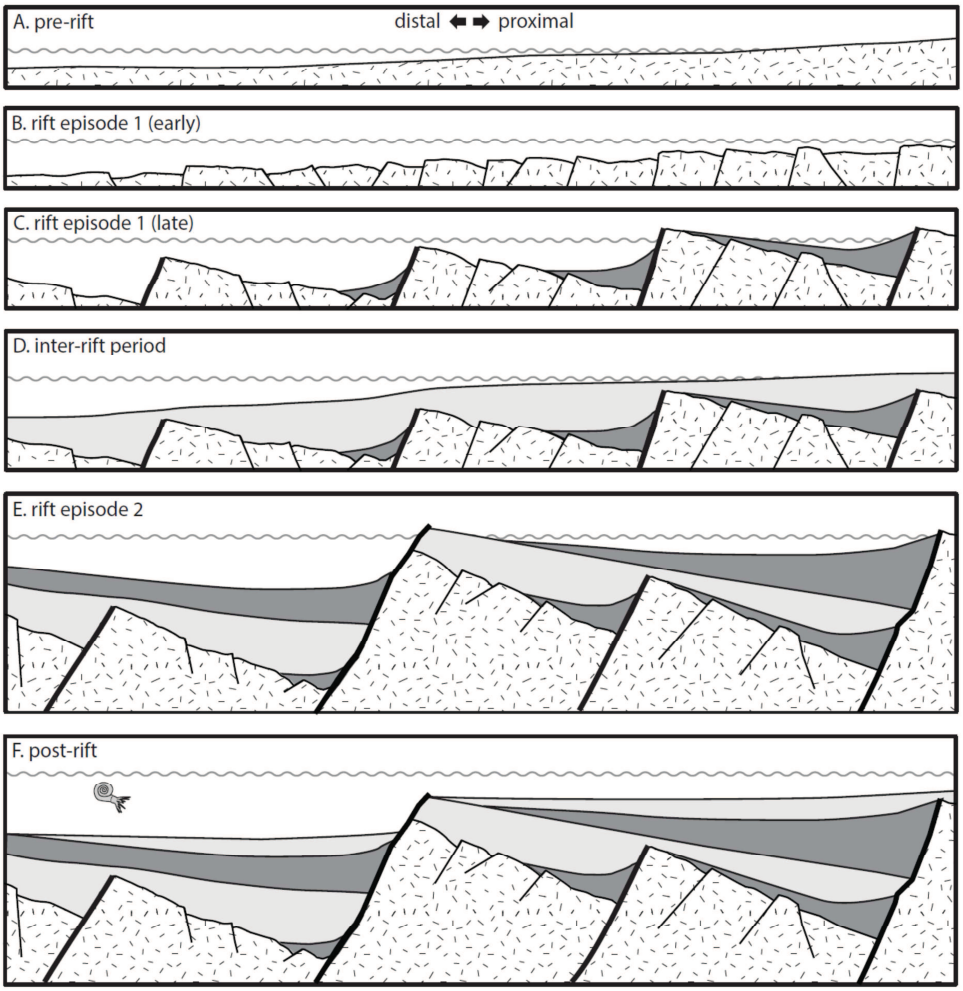

Figure 1. *Conceptual model for specific features of relatively proximal and distal basins formed during two rift episodes, separated by an inter-rift period, somewhat based on the Middle Jurassic to Late Cretaceous evolution of the North Trøna and Ribban Basins. Dark- and light grey represent syn-rift and inter-rift sedimentary fill, respectively.*

5.3 Towards a generic model for the evolution of normal faults during multiple rift episodes

Fault evolution during single rift episodes represents a more or less continuous process starting with an inception stage, followed by linkage and finally rift climax (Cowie et al., 2000). It has been pointed out by Bell et al. (2014) that in multi-episodic rift basins, the process of inception, linkage and climax is repeated and that no generic models exist yet for describing repetitive rejuvenation of faults in multi-episodic rifts. The evolution of long-lived normal faults that develop during multiple rift episodes (such as the Vesterdjupet Fault Zone) can be compared to normal faults that form in a single episode (e.g. the Middle-Late Jurassic rift episode in the northern North Sea; McLeod et al, 2000). Certain differences between single-episode and multi-episode segmented normal faults are listed below:

- Through-going, linked normal faults are prone to form zigzag geometries, being composed of segments formed during different rift episodes.

  Our proposed reconstruction of the evolution of the Vesterdjupet Fault Zone (**paper 2**) shows that a (likely) change in extension direction between the Early Triassic and Late Jurassic rift episodes facilitated linkage of widely spaced Triassic faults, in coherence with the models of multiphase, non-coaxial extension of Henza et al. (2011). It can be assumed that two rift episodes, being separated by a long period of relative tectonic quiescence, are more likely to have a different extension vector than two rift phases within a single episode. This is for instance the case for the Taranaki Basin (Giba et al., 2012), the St. Lawrence rift system (Rocher et al., 2003) and the East African rift system (Bosworth, 1992).

- A rift episode that selectively reactivates buried, through-going faults of foregoing rift episode(s) is characterised by early localisation of strain. High strain rates follow from the fact that displacement is accumulated on only a few structures.

  Inactive faults become buried during inter-rift periods. In the case of the Lofoten margin, the linked Triassic/Jurassic fault zone that formed the

precursor to the Vesterdjupet Fault Zone had become covered by c. 1-2 km of Lower Cretaceous strata before renewed extension took place in the middle Cretaceous. This rift episode was characterised by a minor initiation phase that was quickly succeeded by the climax phase. Selective reactivation of through-going elements of the Triassic/Jurassic fault framework resulted in the early establishment of a long, single slip surface as predicted by the coherent fault model (**paper 2**).

The Clavering-Dombjerg-Thomsenland Fault Zone that forms the main border fault to the Wollaston Forland Basin in East Greenland has a Palaeozoic origin (Surlyk, 1990). During the Late Jurassic to Early Cretaceous rift episode, strain was localised on this fault zone (and a few others) which became reactivated and behaved as a through-going, c. 100 km long normal fault (**paper 4**; Surlyk, 1978).

- Reactivation of previously linked, deeply buried zigzag fault zones produce gently curving faults traces at surface.

  Faults of the foregoing rift episode become buried during inter-rift periods. In the case of the North Træna Basin, this is particularly true for the early Cretaceous, when the Triassic/Jurassic fault framework is buried by more than a kilometre of inter-rift strata. When the Vesterdjupet Fault Zone becomes reactivated during late Albian extension it assumes a curved geometry, lacking the sharp corners that are observed between some of the Triassic and Jurassic fault segments (**paper 2**). A possible explanation for this phenomenon is given by Kettermann & Urai (2015), who used physical models of normal faulting to demonstrate how the presence of overburden influences structural style. These workers noticed a change in failure mode from tensile to shear in experiments with increasing overburden. Shear failure produced curved fault traces rather than sharp changes in strike. Figure 2 shows how this process could explain the difference in curvature of faults between the Early Triassic (Time I), Late

Jurassic (Time II) and middle Cretaceous (Time III) due to repeated burial and reactivation of faults.

These differences are, for the most part, a consequence of long inter-rift periods during which faults become buried and changes may occur in the regional stress-field. Subsequent rift episodes during which strain is accommodated by reactivating through-going faults from a foregoing episode are characterised by fast (re-)establishment of laterally extensive slip surfaces. Early accumulation of displacement on the major fault zones results in pronounced fault block rotation, documented in **papers 3 and 4**. Rotation of wide fault blocks has a more pronounced effect on basin physiography than if displacement was distributed over many small faults. Rotation may force drainage systems to redirect and thus exerts a major control on depositional style. The development of long spurs and deep hanging wall depocentres over strongly rotated fault blocks thus seems to be a feature of multi-episodic rifts rather than single-episode rifts, and has profound consequences for rift fill.

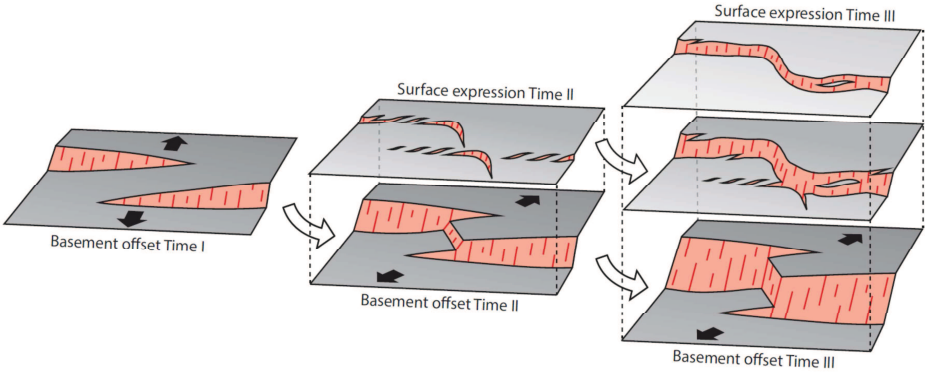

Figure 2. *Conceptual model for the repetitive (oblique) reactivation and linkage of buried faults. The situation prior to reactivation is shown at Time I, this level is referred to as 'basement'. During the first phase of oblique reactivation (Time II) the ramp is breached at depth and crescent-shaped faults develop at surface. The original basement faults are reactivated as well, forming en-echelon arrays at surface. During a secondary phase of reactivation (Time III) a single, segmented fault zone develops at surface. At depth, the already breached ramp at basement level moves as a single feature while most of the isolated surface structures from Time II have linked up at the intermediate level.*

5.3 Possible explanation for contrasting plan-view geometries of major rift faults

In the Lofoten margin, faults that first formed as part of the Triassic rift episode strike NNE-SSW predominantly, whereas faults incepted in the Jurassic and Cretaceous rift episodes are striking NE-SW **(paper 2**). As a consequence, the Cretaceous Vesterdjupet Fault Zone which is strongly influenced by Triassic precursor faults, is made up predominantly of NNE-SSW-striking segments with one NE-SW-striking jog. We discussed how this geometry follows physical analogue models of non-coaxial extension of Henza et al. (2011; **paper 2**). The West Lofoten Border Fault Zone exhibits a pattern of long (40 km) NE-SW trending segments alternating with relatively short (15 km) NNE-SSW trending steps (Fig. 3). In **paper 1** we interpret the southern Ribban Basin as having formed over the central dome of a metamorphic core complex that was affected less by Triassic rifting. This suggests that no strong NNE-SSW-trending fault grain exists in the area where the West Lofoten Border Fault Zone formed. We speculate that the dominance of NE-SW-oriented structures of this fault zone may be a consequence of this supposedly weaker pre-existing NNE-SSW: when the West Lofoten Border Fault Zone formed during Jurassic and mostly middle Cretaceous rifting, there were fewer, if at all, Triassic faults to reactivate, and most segments followed the Jurassic/Cretaceous NE-SW trend.

Unfortunately, the lack of wells and limited seismic dataset over the Ribban Basin is currently insufficient to confirm these speculations. Should new data become available that would indicate absence of a well-developed Triassic fault grain, then the evolution of the West Lofoten Border Fault Zone is in good agreement with the results of Henza et al. (2011), as it can be correlated to for instance model B (Henza et al., 2011) that is characterised by a weak 1st phase extension (correlated to the Triassic rift episode in our case) and a strong 2nd phase extension (correlated to the Jurassic/Cretaceous rift episodes in our case). Fault zones of model B show a definite dominance of segments incepted during second phase extension. Once more well- and seismic data becomes available, this hypothesis could be tested.

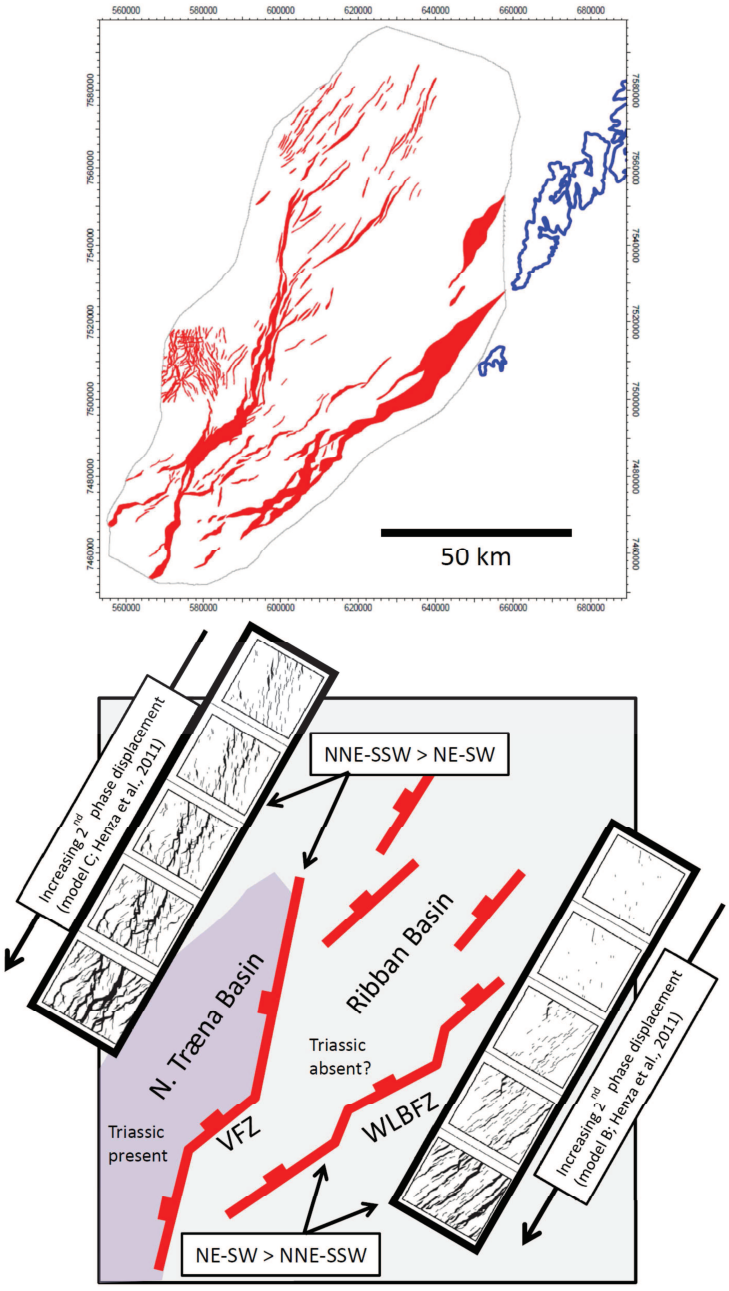

Figure 3. *Fault polygons of the Base Cretaceous horizon, mapped using seismic reflection data over the North Træna- and Ribban Basins. The Cretaceous fault zones of the Lofoten margin exhibit a two-fold distribution in terms of their plan-view geometry. We observe a strong correlation between i) the presence of a well-developed Triassic fault grain and ii) Cretaceous faults consisting of predominantly NNE-SSW-striking segments. Where an ancestral early Triassic structural grain is speculated to be absent, on the other hand, Cretaceous composite faults are mostly composed of NE-SW-striking segments.*

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