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Analogue experiments on releasing and restraining bends and their application to the study of the Barents Shear Margin

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Abstract:
The Barents Shear Margin separates the Svalbard and Barents Sea from the North Atlantic. It includes one northern (Hornsund Fault Zone) and a southern (Senja Fracture Zone) margin segment in which structuring was dominated by dextral shear. These segments are separated by the Vestbakken Volcanic Province that rests in a releasing bend position between the two. During the break-up of the North Atlantic the plate tectonic configuration was characterized by sequential dextral shear, extension, contraction and inversion. This generated a complex zone of deformation that contain several structural families of over-lapping and reactivated structures Although the convolute structural pattern associated with the Barents Shear Margin has been noted, it has not yet been explained in this framework.
A series of crustal-scale analogue experiments, utilizing a scaled stratified sand-silicon polymer sequence, serve to study the structural evolution of the shear margin in response to shear deformation along a pre-defined boundary representing the geometry of the Barents Shear Margin and variations in kinematic boundary conditions of subsequent deformation events, i.e. direction of extension and inversion.
The observations that are of particular significance for interpretating the structural configuration of the Barents Shear Margin are:
1)The experiments reproduced the geometry and positions of the major basins and relations between structural elements (fault and fold systems) as observed along and adjacent to the Barents Shear Margin. This supports the present structural model for the shear margin.
2) Several of the structural features that were initiated during the early (dextral shear) stage became overprinted and obliterated in the subsequent stages.
3) Prominent early-stage positive structural elements (e.g. folds, push-ups) interacted with younger (e.g. inversion) structures and contributed to a complex final structural pattern.
4) All master faults, pull-part basins and extensional shear duplexes initiated during the shear stage quickly became linked in the extension stage, generating a connected basin system along the entire shear margin at the stage of maximum extension.
5) The fold pattern generated during the terminal stage (contraction/inversion became dominant in the basinal areas and was characterized by fold axes with traces striking parallel to the basin margins. These folds, however, most strongly affected the shallow intra-basinal layers.
This is in general agreement with observations in previous and new reflection seismic data from the Barents Shear Margin.

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Plain language summary:
The Barents Shear Margin defines the border between the relatively shallow Barents Sea that is situated on a continental plate, and the deep ocean. This margin evolution history was probably influenced by the plate tectonic reorganizations. From scaled experiments we deducted several types of structures (faults, folds and sedimentary basins) that helps us to improve the understanding of the history of the opening of the North Atlantic.

Key words: Analogue experiments, dextral strike-slip, releasing and restraining bends, multiple folding, Barents Shear Margin**,** basin inversion

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Introduction

Physiography, width and structural style of the Norwegian continental margin vary considerably along its strike (e.g. Faleide et al. 2008, 2015). The margin includes a southern rifted segment between 60° and 70°N and a northern sheared-rifted segment between 70° and 82°N (**Figure 1A**). The latter coincides with the ocean-ward border of the western Barents Sea and Svalbard margins (e.g. Faleide et al. 2008) and is referred to here as "the Barents Shear Margin". This segment coincides with the continent-ocean transition (COT) of the northernmost part of the North Atlantic Ocean, and its configuration is typical for that of transform margins where the structural pattern became established in an early stage of shear, later to develop into an active continent-ocean passive margin (Mascle & Blarez 1987; Lorenzo 1997; Seiler et al. 2010; Basile 2015; Nemcok et al. 2016).

Late Cretaceous - Palaeocene shear, rifting, breakup and incipient spreading in the North Atlantic was associated with voluminous magmatic activity, resulting in the development of the North Atlantic Volcanic Province (Saunders et al. 1997; Ganerød et al. 2010; Horni 2017). According to its tectonic development, the Barents Shear Margin (**Figure 1B**) incorporates, or is bordered by, several distinct structural elements, some of which are associated with volcanism and halokinesis.

The multistage development combined with a complex geometry caused interference between structures (and sediment systems) in different stages of the margin development. Such relations are not always obvious, but interpretation can be supported by the help of scale-models. In combining the interpretation of reflection seismic data and analogue modeling, therefore, we investigate structures generated in (initial) dextral shear, the development into seafloor spreading and subsequent contraction in this process, the later stages of which were likely influenced by plate reorganization (Talwani & Eldholm 1977, Gaina et al. 2009, see also see also Vågnes et al. 1998; Pascal & Gabrielsen 2001; Pascal et al. 2005; Gac et al. 2016) or other far-field stresses (Doré & Lundin 1996; Lundin & Doré 1997; Doré et al. 1999; 2016; Lundin et al. 2013). The present experiments were designed to illuminate the structural complexity affiliated with multistage sheared passive margins, so that the significance of structural elements like fault and fold systems observed along the Barents Shear Margin could be set into a dynamic context.

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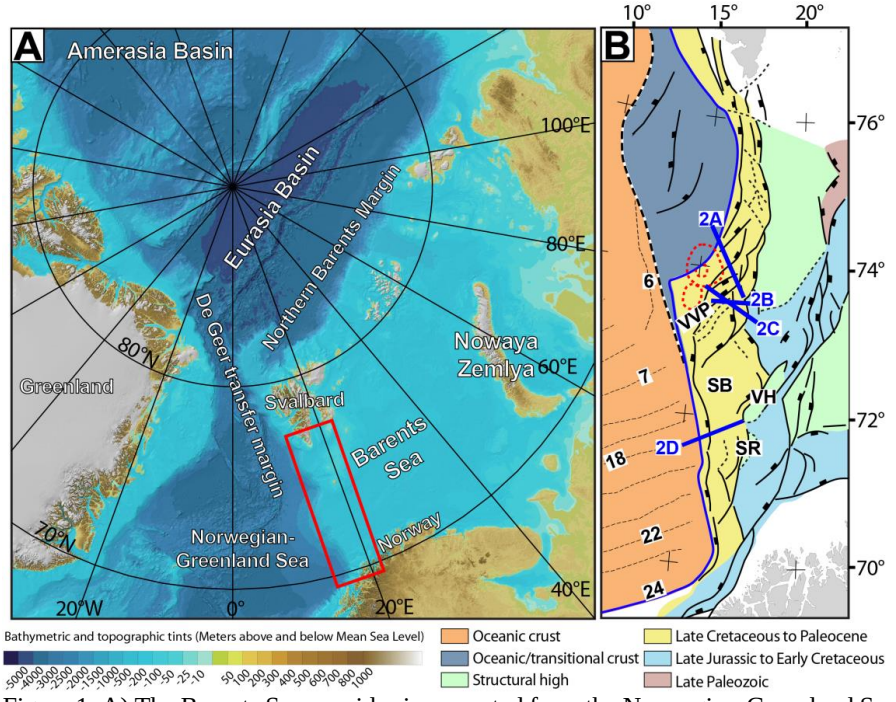

Figure 1: A) The Barents Sea provides is separated from the Norwegian-Greenland Sea by the de Geer transfer margin. Red box shows the present study area. B) Structural map Barents Sea shear margin. Note segmentation of the continent-ocean transition. Abbreviations: HFZ=Hornsund Fault Zone, KFC = Knølegga Fault Complex, SFZ=Senja Shear Zone, SR=Senja Ridge, SB = Sørvestsnaget Basin, VVP = Vestbakken Volcanic Province.

Regional background

In the following sections we provide definitions and a short description of the most important structural elements constituting the study area. All structural elements described below are displayed in **Figure 1B**.

The Barents Shear Margin was preceded by the "De Geer Zone" (Eldholm et al. 1987; 2002; Faleide et al. 1988; Breivik et al. 1998; 2003). Together with its conjugate Greenland counterpart it carries the evidence of an extensive period of structuring, starting with post-Caledonian (Devonian) extension and culminating with Cenozoic break-up of the North Atlantic (e.g. Brekke 2000; Gabrielsen et al. 1990; Faleide et al. 1993; Gudlaugsson et al. 1998). Two shear margin segments that are separated by a central rift-dominated segment can be identified in the Barents Shear Margin (Myhre et al. 1982; Vågnes 1997; Myhre & Eldholm 1988; Ryseth et al. 2003; Faleide at al.

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1988; 1993; 2008). Each segment maintained a particular signature concerning the structural and magmatic characteristics of the crust during its development. Of these the Senja Shear Margin is the southernmost segment, originally termed the Senja Fracture Zone by Eldholm et al. (1987). Particularly the hanging wall west of the Knølegga Fault Complex of the Barents Shear Margin was affected by wrench deformation as seen from several push-ups and fold systems (Grogan et al. 1999; Bergh & Grogan 2003). Here, NNW-SSE-striking folds interfere with folds with NE-SW-striking axes (Giennenas 2018). Strain partitioning may also have affected some of the other shear zone segments of the study area (Kristensen et al. 2017).

The Senja Shear Margin was active during the Eocene opening of the Norwegian-Greenland Sea during dextral shear that was accompanied splitting out slivers of continental crust that became isolate units embedded by oceanic crust during seafloor spreading (Faleide et al 2008). The Senja Shear Margin coincides with the western margin of a basin system that is characterized by significant crustal thinning and extreme sedimentary thicknesses that may approach 18-20km. This part of the shear margin was characterized by a composite architecture even at the earliest stages of its development (Faleide et al. 2008). Subsequently shearing contributed to the development of releasing and restraining bends, associated pull-apart-basins, neutral strike-slip segments, flower-structures and fold-systems (*sensu* Crowell 1974a,b; Biddle & Christie-Blick 1985a,b; Cunningham & Mann 2007a,b). The structuring of the margin was complicated by active halokinesis (Knutsen & Larsen 1997; Gudlaugsson et al. 1998; Ryseth et al. 2003).

The Hornsund Fault Zone and West Spitsbergen Fold-and Thrust Belt form the northernmost segment of the Barents Shear Margin and coincides with the northern continuation of the De Geer Zone and the Senja Shear Margin. The presently distinguishable master fault of this system is the Hornsund Fault Zone, which together with the West Spitsbergen fold-and-thrust-belt provides a classical setting for transpression and strain partitioning (Harland 1965; 1969; 1971; Lowell 1972; Gabrielsen et al. 1992; Maher et al. 1997; Leever et al. 2011 a,b). Plate tectonic reconstructions suggest that the plate boundary accommodated c. 750 km along-strike displacement and 20-40 km of shortening in the Eocene (Bergh et al. 1997; Gaina et al. 2009).

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The Sørvestsnaget Basin occupies the area east the COT between 71 and 73°N and is characterized by an exceptionally thick Cretaceous-Cenozoic sequence (Gabrielsen et al. 1990). To the west it is delineated by the Senja Shear Margin and to the northeast it is separated from the Bjørnøya Basin by the southern part of the Knølegga Fault Complex (Faleide et al. 1988). The Senja Ridge coincides with its southeastern border, whereas the Vestbakken Volcanic Province is situated to its north. An episode of Cretaceous rifting in the Sørvestsnaget Basin seems to have climaxed in the Cenomanian-middle Turonian (Breivik et al. 1998) to become succeeded by Late Cretaceous-Palaeocene fast sedimentation (Ryseth et al. 2003). Particularly the later stages of the basin development were likely strongly influenced by the opening of the North Atlantic (Hanisch 1984; Brekke & Riis 1987). Salt diapirism did also contribute to structuring of this basin (Perez-Garcia et al. 2013).

The Senja Ridge runs parallel to the continental margin and coincides with the western border of the Tromsø Basin. It is characterized by a N-S-trending gravity anomaly which are interpreted as buried mafic-ultramafic intrusions which are associated with the Seiland Igneous Province (Fichler & Pastore 2022). The structural development of the Senja Ridge has been linked to shear affiliated with the development of the shear margin (Riis et al. 1986).

The Knølegga Fault Complex can be seen as a part of the Hornsund fault system extending from the southern tip of Spitsbergen (Gabrielsen et al. 1990). It trends NNE-SSW to N-S and defines the western margin of the Stappen High. The vertical displacement approaches 6 km. Although the main movements along the fault may be Tertiary of age, it is likely that it was initiated much earlier. The Tetiary displacement may have had a lateral (dextral) component (Gabrielsen et al. 1990).

The Vestbakken Volcanic Province is the central topic of the present contribution. It represents the rifted segment of the Senja Shear Margin and links the sheared margin segments that are situated to the north and south of it and occupies a typical right-double stepping (eastward) releasing-bend-setting. Prominent volcanoes and sill-intrusions display significant magmatic activity, and three distinct volcanic evens are distinguished in the Vestbakken Volcanic Province (Jebsen & Faleide 1998; Faleide et

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al. 2008; Libak et al. 2012). The area has been affected by complex tectonics and both extensional and contractional structures are observed. The Vestbakken Volcanic Province is delineated towards the east by an extensional top-west fault zone that parallels the Knølegga Fault Complex). The interior of the Vestbakken Volcanic Province is dominated by NE-SW-striking extensional faults and associated fault blocks. Positive structural elements include inverted fault blocks, and wide-angle (> 20 km) anticlines (roll-over anticlines?) and domes that are overprinted by faults and folds with amplitudes and wavelengths on the hundred- and km-scales.

The eastern boundary fault (EBF) is a top-west normal fault with a regional NNE-SSW strike, consisting of two separate, hard-linked segments. Its northern segment dips more steeply to the WNW than the southern segment. The total vertical displacement as measured on the early Eocene level is in the order of 300 msec (450m), and the upper part of the hanging wall displays a normal drag modified by hanging wall tight anticline suggesting post early Miocene inversion. Several normal, dominantly NE-SW-striking NW-facing normal faults transect the hanging wall of the EFB-fault. The Central Fault (CF) is the largest of those and is hard-linked to the central segment of the EFB-fault is the largest of those. The Central Fault is the most prominent fault of a NW-SE-striking fault population that characterizes the entre Vestbakken Volcanic Province. Three episodes of Cenozoic extensional faulting were identified in the Vestbakken Volcanic Province: (i) a late Paleocene-early Eocene event, which correlates in time with the continental break-up in the Norwegian-Greenland Sea, (ii) an early Oligocene event is tentatively correlated to plate reorganization around 34 Ma activated mainly NE-SW striking faults and (iii) an extensional Pliocene event. Evidence of volcanic activity coincide with the first two of these events. The Vestbakken Volcanic Province is constrained to its east by the eastern boundary fault (EBF in **Figure 1B**), that is a part of the Knølegga Fault Complex, separating the Vestbakken Volcanic Province from the marginal Stappen High further to the east. To the south and southeast the Vestbakken Volcanic Province drops gradually into the Sørvestsnaget Basin across the southern extension of the eastern boundary fault and its associated faults. To the west and north the area is delineated by the continent – ocean boundary/transition (marked as COB in Fig. 4.1). The Vestbakken Volcanic Province includes both extensional and contractional structures (e.g. Jebsen & Faleide, 1998; Faleide et al., 2008; Blaich et al., 2017). Cenozoic tectonic activity has left its imprint at the eastern part of the study area. All other faults in this map are secondary faults, mainly acting as accommodation

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structures to the master faults. Starting from the southern part of the area and south of the well site, a population of secondary faults is expressed as anastomosing faults traces.

Reflection seismic data

The data set of this study includes 2D seismic reflection data from several surveys and well data in the Vestbakken Volcanic Province. Data coverage is less dense in northern part of the study area. Typical spacing of seismic lines is 4km. Well 7316/5-1 was used to correlate the seismic data with formation tops in the study area whereas published paper based correlations provided calibration and age of each seismic horizon mapped (e.g. Eidvin et al., 1993; 1998 Ryseth et al., 2003). Three stratigraphic groups are present in the well; the Nordland Group (473 - 945 m); the Sotbakken Group (945-3752m) and Nygrunnen Group (3752-4014m) (Eidvin et al., 1993; 1998; www.npd.com).

Fold families

Several folds of regional significance (with axial traces that can be followed along strike for 2-3 km or more) occur in the Vestbakken Volcanic Province. The folds commonly are situated in the hanging walls of extensional fault, some of which bear the characteristics of tectonic inversion. The fold axial traces parallel the fault traces or are situated in the strike-continuation of such. It therefore seems obvious that the structural grain, as defined by the thick-skinned master faults strongly influenced the positions of the subsequent folds. The continuity of these structures remains obscure due to spacing of refection seismic lines, so each fold may include undetected overlap zones or axial off-sets that have not been detected. The folds were identified on the lower Eocene, Oligocene and lower Miocene levels. All the mapped folds are either positioned in the hanging walls of extensional (sometimes inverted) master faults or are dissected by younger faults with minor throws.

Three basic fold families were identified in the Vestbakken Volcanic Province by Giennenas (2018): *Fold family 1* **(Figure 2)** consists of gentle to open anticline-syncline pairs with upright to slightly inclined axial planes, sometimes with shallowly plunging fold axes and saddle points, so that the folds are not strictly cylindrical. Folds of this

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family strikes dominantly NE-SW to NNE-SSW and are generally situated at some distance from the master basin margin faults and in the central parts of the Vestbakken Volcanic Province where larger faults are less abundant. The wavelengths are in the order of 3-10 km and the amplitudes may reach 400 m. The fold flanks sometimes display smaller open folds with wavelengths on the hundred-meter-scale that may be parasitic, whereas the central parts are commonly broken by post-folding steep brittle normal faults that define separate fault zones that are separate from the major folds along strike (see Fold family 3 below). *Fold family 2* includes folds with inclined axial planes with dominantly long NW-limbs and short SE-limbs (**Figure 2**), which are more common along the basin margin and in affiliation with low-angle intra-basin reverse faults. These generally have the characteristics of fault-propagation folds and are positioned in the hanging walls with steep, inverted normal faults. These are characterized of axial planes with dips of up to 45 deg) and snake-head-geometries commonly found in the hanging walls of master faults (**Figure 2A, B**). Fold family includes anticline-syncline pairs with fold axes that are parallel and are situated more distally tothe eastern boundary fault (EBF) and are found internally in extensional fault blocks. The fold axes of the latter sub-family have up-right axial planes and are accordingly generally oriented N-S

Strike-slip systems and analogue shear experiments

Shear margins and strike-slip systems are structurally complex and highly dynamic, meaning that the incipient and mature stages of strike-slip deformation commonly display a variety of geometries (e.g. Graymer et al. 2007) making it hard to comprehend the full complexity solely through fieldwork (e.g. Crowell 1962, 1974a,b; Woodcock & Fischer 1986; Mousloupoulou et al. 2007; 2008). Analogue

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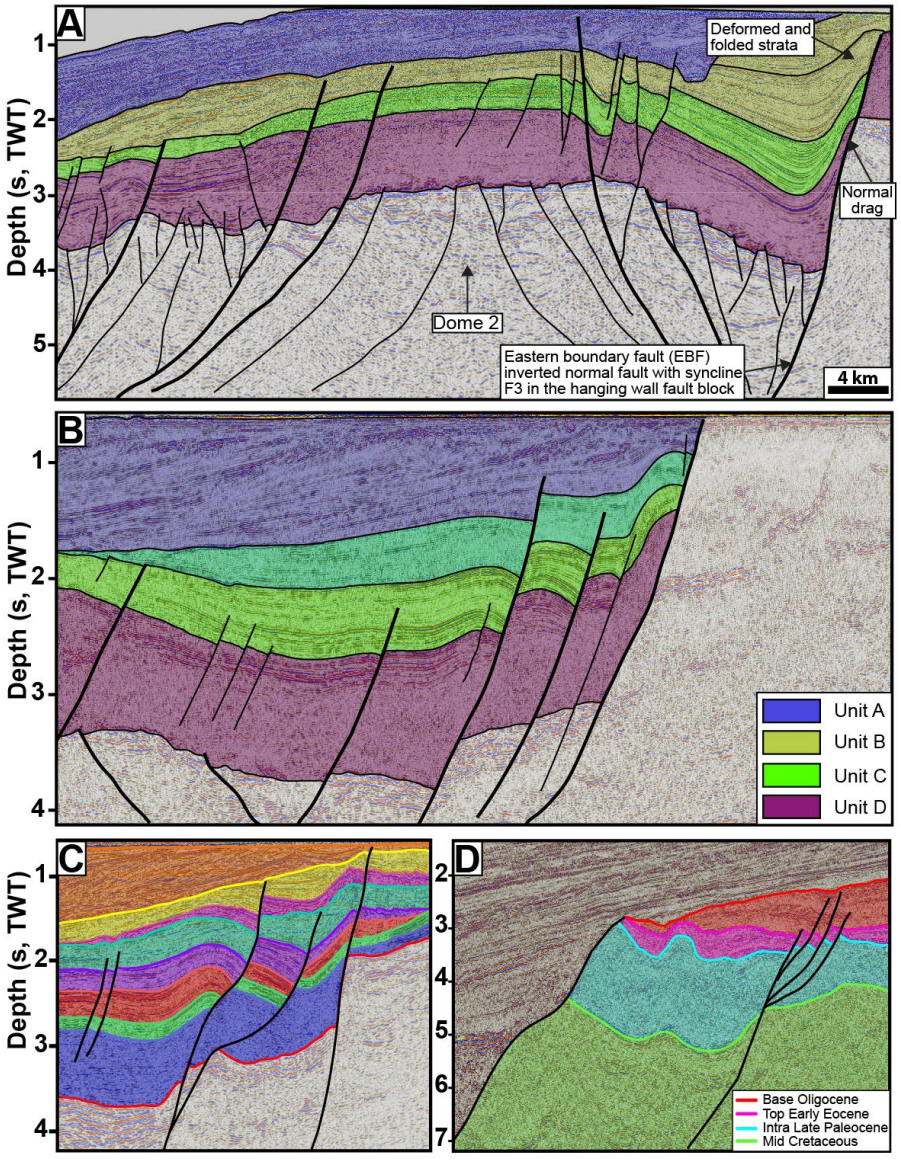

Figure 2: Seismic examples, Vestbakken Volcanic Province. A) Gentle, partly collapsed NE-SW-striking anticline/dome of fold family 1 (Giannenas 2018) of uncertain origin in the eastern terrace domain of the southern Vestbakken Volcanic Province. This may be a remnant, rotated PSE-1-structure (see text for explanation). B,C) Assymetrical folds (fold family 2; Giannenas 2018) situated along the eastern margin of the Vestbakken Volcanic Province. These may represent primary SPE-5-structures focused in the hangingwalls along margins of master fault blocks, or reactivated SPE-2-structures. D) trains of symmetrical folds with upright fold axes (corresponding to PSE-5-structures are preserved inside larger fault blocks. See text for explanation of SPE-structures.

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models illustrate such complexity well and therefore attracted the attention of early workers in this field (e.g. Cloos 1928; Riedel 1929) and have continued to do so until today. Early experimental works mostly utilized one-layer ("Riedel-box") models (e.g. Emmons 1969; Tchalenko 1970; Wilcox et al. 1973), which were soon to be expanded by the study of multilayer systems (e.g. Faugère et al. 1986; Naylor et al. 1986; Richard et al. 1991; Richard & Cobbold 1989, 1995; Schreurs 1994, 2003; Manduit & Dauteuil 1996; Dateuil & Mart 1998; Schreurs & Colletta 1998, 2003; Ueta et al. 2000; Dooley & Schreurs 2012). The systematics and dynamics of strike-slip systems have been focused upon in a number of summaries like Sylvester (1985, 1988); Biddle & Christie-Blick (1985a,b); Cunningham & Mann (2007); Dooley & Schreurs (2012); Nemcok et al. (2016) and Peacock et al. (2016). Concepts and nomenclature established in these works are used in the following descriptions and analysis. Also, following Christie-Blick & Biddle (1985a,b) and Dooley & Schreurs (2012) we apply the term Principal Deformation Zone (PDZ) for the junction between the movable polythene plates underlying the experiment. The contact between the fixed and movable base defined a non-stationary velocity discontinuity ("VD"; Ballard et al. 1987; Allemand & Brun 1991; Tron & Brun 1991).

Several experimental works have particularly focused on the geometry and development of pull-apart-basins in releasing bend settings (Mann et al. 1983; Faugére et al. 1983; Richard et al. 1995; Dooley & McClay 1997; Basile & Brun 1999; Sims et al. 1999; Le Calvez & Vendeville 2002; Mann 2007; Mitra & Paul 2011). The pull-apart basin was described by Burchfiel & Stewart (1966) and Crowell (1974a,b) as formed at a releasing bend or at a releasing fault step-over along a strike-slip zone (Biddle & Christe-Blick 1985a,b). This basin type has also been termed "rhomb grabens" (Freund 1971) and "strike-slip basins" (Mann et al. 1993) and is commonly considered to be synonymous with the extensional strike-slip duplex (Woodcock & Fischer 1986; Dooley & Schreurs 2012). In the descriptions of our experiments, we found it convenient to distinguish between extensional strike-slip duplexes in the context of Woodcock & Fischer (1986) and Twiss & Moores 2007, p. 140-141;) and pull-apart basins (rhomb grabens: Crowell 1974a,b; Aydin & Nur 1993) since they reflect slightly different stages in the development in our experiments (see discussion).

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Experimental setup

To study the kinematics of complex shear margins, a series of analogue experiments were performed at the tectonic modelling laboratory (TecLab) of Utrecht University, The Netherlands. All experiments were built on two overlapping 1 mm thick plastic sheets (each 100 cm long and 50 cm wide) that were placed on a flat, horizontal table surface. The boundary between the underlaying movable and overlaying stationary plastic sheets had the shape of the mapped continent-ocean boundary (COB; **Figure 1B**). The moveable sheet was connected to an electronic engine, which pulled the sheet at constant velocity. The modelling material was then placed on these sheets where the layers on the stationary sheet represent the continental crust including the continent-ocean transition (COT) whereas the those on the mobile sheet represents the oceanic crust. The model layers are confined by aluminum bars along the long sides and sand along the short sides (**Figure 3A**). Continental crust tapers off towards the oceanic crust simulating the ocean-continent transition (**Figure 3B**) were included in all models.

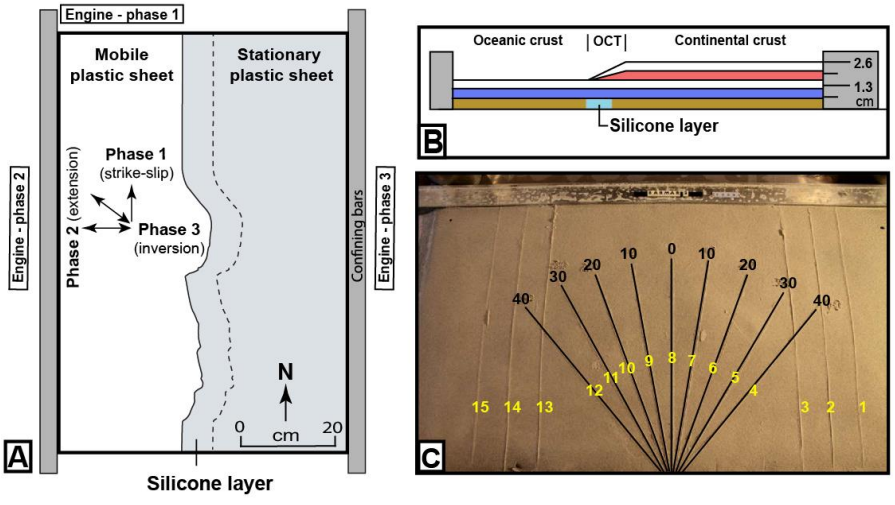

Figure 3: A) Schematical set-up of BarMar3-experiment as seen in map view. B) Section through same experiment before deformation, indicating stratification and thickness relations. C) Standard positions and orientation for sections cut in all experiments in the BarMar-series. Yellow numbers are section numbers. Black numbers indicate angle between the margins of the experiment (relative to N-S) for each profile.

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The pre-cut shape of the plate boundary includes major releasing bends positioned so that they correspond to the geometry of the COB and the three main structural segments of the Barents Shear Margin as follows. *Segment 1* of the BarMar-experiments (**Figure 4**) contained several sub-segments with releasing and restraining bends as well as segments of "neutral" (Wilcox et al. 1973; Mann et al. 1983; Biddle & Christie-Blick 1985b) or "pure" (Richard et al. 1991) strike-slip. *Segment 2* had a basic crescent shape, thereby defining a releasing bend at its southern margin in the position similar to that of the Vestbakken Volcanic Province, that merged into a neutral shear-segment along the strike of, whereas a restraining bend occupied the northern margin of the segment. *Segment 3* was a straight basement segment, defining a zone of neutral shear and corresponds to the strike-slip segment west of Svalbard (**Figure 1**).

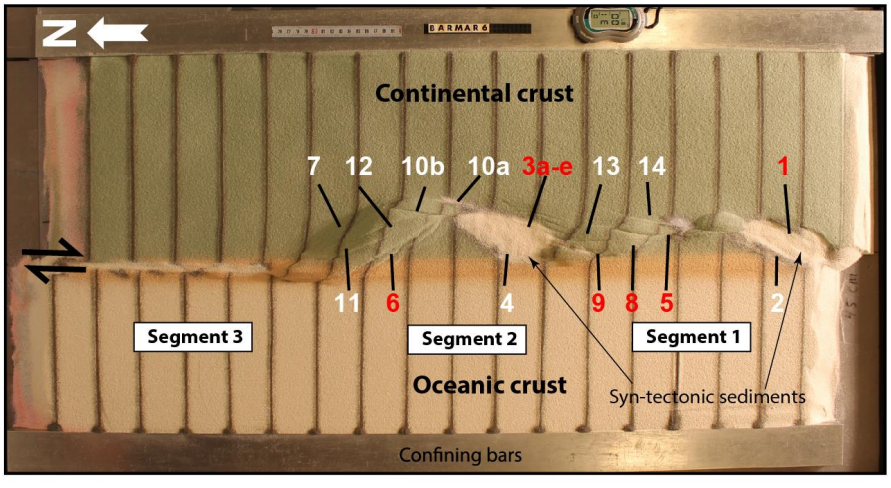

Figure 4: Position of segments and major structural elements as referred to in the text and subsequent figures (see particularly Figures 5 and 6). This example is taken from the reference experiment BarMar6. All experiments BarMar6-9 followed the same pattern, and the same nomenclature was used in the description of these experiments.

The experiments included three stages of deformation with constant rates of movement of the mobile sheet at 10 $cmhr^{-1}$ in all three stages. Dextral shear was applied in the *first phase* in all experiments by pulling the lower plastic sheet by 5cm. In the *second phase* the left side of the experiment was extended by 3 cm orthogonally (BarMar6) or obliquely (325 degrees; BarMar 8 & 9) to the trend of the shear margin, whereas plate motion was reversed during the *third phase of deformation*, leading to inversion of

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earlier formed basins that had been developed in the strike-slip and extensional phases. Sedimentary basins that develop due to strike-slip (phase 1) or extension (phase 2) have been filled with layers of colored feldspar sand by sieving. These layers are primarily important for discriminating among deformation phases and thus act as marker horizons. Phase 3 was initiated by inverting the orthogonal (BarMar6) or oblique (BarMar 8 & 9,) extension of Phase 2 as a proxy for ridge-push that likely was initiated when the mid-oceanic ridge was established in Miocene time in the North Atlantic (Moser et al., 2002; Gaina et al. 2009). Contraction generated by ridge-push has been inferred from the mid Norwegian continual shelf (Vågnes et al. 1998; Pascal & Gabrielsen 2001; Faleide et al. 2008; Gac et al. 2016) and seems still to prevail in the northern areas of Scandinavia (Pascal et al., 2005), although far-field compression generated by other processes have been suggested (e.g. Doré & Lundin 1996).

Coloured layers of dry feldspar sand represent the brittle oceanic and continental crust. This material has proven suitable for simulating brittle deformation conditions (Willingshofer et al., 2005; Luth et al. 2010; Auzemery et al., 2021) and is characterized by a grain size of 100-200 □m, a density of 1300 kgm^{-3}, a cohesion of ~16-45 Pa and a peak friction coefficient of 0.67 (Willingshofer et al. 2018). Additionally, a 8 mm thick and of variable width corresponding to the mapped transition zone of 'Rhodorsil Gomme GSIR' (Sokoutis, 1987) silicone putty mixed with fillers was used as a proxy for the thinned and weakened continental crust at the ocean-continent transition (**Figure 1B and 3A,B**). This Newtonian material (n=1.09) has a density of 1330 $kgm^{-3}$and a viscosity of $1.42x10^{4}$ Pa.s.

The experiments have been scaled following standard scaling procedures as described by Hubbert (1937), Ramberg (1967) or Weijermars and Schmeling (1986), assuming that inertia forces are negligible when modelling tectonic processes on geologic timescales (see Ramberg (1981) and Del Ventisette et al., (2007) for a discussion on this topic). The models were scaled so that 10 mm in the model approximates c. 10 km in nature yielding a length scale ratio of $1.00E^{-6}$. As such, the model oceanic and continental crusts scale to 18 and 26 km in nature, respectively, which, although slightly overestimating the most intensely thinned oceanic crust (10-12 km) is in full agreement with the estimated thickness of the thinned oceanward segment of the continental crust (30-20 km Breivik et al. 1998).

The brittle crust, dry feldspar sand, deforms according to the Mohr-Coulomb fracture criterion (Horsfield 1977; Mandl et al. 1977; McClay 1990; Richard et al. 1991;

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Klinkmüller et al. 2016), whereas silicone putty promotes ductile deformation and folding. The geometry applied in the present experiments is accordingly well suited for the study of the COB in the Barents Shear Margin (Breivik et al. 1998).

When complete, the experiments were covered with a thin layer of sand further to stabilize the surface topography before the models were saturated with water and cross-sections that were oriented transverse to the velocity discontinuity were cut in a fan-shaped pattern (**Figure 3C**). All experiments have been monitored with a digital camera providing top-view images at regular time intervals of one minute.

All experiments performed were oriented in a N-S-coordinate framework to facilitate comparison with the western Barents Sea area and had a three-stage deformation sequence (dextral shear – opening – closure). All descriptions and figures relate to this orientation. It was noted that all experiments reproduced comparable basic geometries and structural types, demonstrating robustness against variations in contrasting strength of the "ocean-continent"-transition zone, which included by a zone of silicone putty with variable width below a eastward thickening sand-wedge (**Figure 3B**) and changing displacement velocities.

Modelling Results

A series of totally nine experiments (BarMar1-9) with the set-up described above was performed. Experiments BarMar1-5 were used to calibrate and optimize geometrical outline, deformation rate, and angles of relative plate movements and are not shown here. The optimized geometries and experimental conditions were utilized for experiments BarMar6-9, of which BarMar6 and 8 (and some examples from BarMar9 and are illustrated here, yielded similar results in that all crucial structural elements (faults and folds) were reproduced in all experiments as described in the text are shown in **Figure 4**.) It is emphasized that the extensional basins affiliated with the extension phase (phase 2) became wider in the orthogonal (BarMar6) as compared to oblique extension experiments (BarMar 8) (**Figures 5 and 6**). Furthermore, the fold systems generated in the experiments that utilized oblique contraction of $325/145^0$ (BarMar8-9) produced more extensive systems of non-cylindrical folds with continuous, but more curved fold traces as compared experiments with orthogonal extension/contraction (BarMar6). The fold axes generally rotated to become parallel to the (extensional)

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master faults delineating the pull-apart basins generated in deformation stage 1 in experiments with an oblique opening/closing angle.

Examples of the sequential development is displayed in **Figures 5 and 6**) and summarized in **Figure 7**.

Elongate positive structural elements with fold-like morphology as seen on the surface were detected during the various stages of the present experiments. The true nature of those were not easily determined until the experiments were terminated and transects could be examined. Such structures included buried push-ups (*sensu* Dooley & Schreurs 2012), antiformal stacks, back-thrusts, positive flower structures, fold trains, and simple anticlines. For convenience, we use the non-genetic term "positive structural elements" termed *PSEm-n* for such structure types as seen in the experiments in the following description.

In the following the deformation in each segment is characterized for the three deformation phases.

Deformation phase 1: Dextral shear stage

Segment 1: Differences in the geometry of the pre-cut fault trace between segments 1, 2 and 3 became evident after the very initial deformation stage. Particularly in segments 1 and 3 an array of oblique *en échelon* folds in between Riedel shear structures (*PSE-1-structures*) oriented c. 145°(NW-SE) to the regional VD rotating into a NNW-SSE-orientation by continued shear (**Figure 8**; see also Wilcox et al. 1973; Ordonne & Vialon 1983; Richard et al. 1991; Dooley & Schreurs 2012). These were simple, harmonic folds with upright axial planes and fold axial traces extending a few cm beyond the surface shear-zone described above. They had amplitudes on the scale of a few millimeters and wavelengths on scale of 5 cm. The PSE-1-structures interfered with or were dismembered by younger developing structures, also causing northerly rotation of individual intra-fault zone lamellae (remnant PSE-1-structures (**Figure 8**). Structures similar to PSE-1-fold arrays are known from almost all strike-slip experiments reported and described in the literature from the early works of (e.g. Cloos 1928; Riedel 1929. See Dooley & Schreurs 2012 for summary) and are therefore not given further attention here. By 0.25 cm of horizontal displacement in segment 1, which included two releasing and restraining bends in combination with strands of neutral shear, a slightly curvilinear

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surface trace of a NE-SW-striking, top-NW normal faultsin the southernmost part of segment 1 developed. This co-existed with the PSE-1-structures and was immediately paralleled by a normal fault with opposite throw (fault 2, **Figure 4**) so that the two faults constrained a crescent- or spindle-shaped incipient extensional shear duplex (**Figures 5B and 6B**; see also Mann et al. 1983; Christie-Blick & Biddle 1985; Mann 2007; Dooley & Schreurs 2012).

A system of *en échelon* separate N-S to NNE-SSE- striking normal and shear fault segments became visible in segment 1 after ca. 1 cm of shear (**Figure 5C,D**). These faults did not have the orientations as expected for R- and R'-shears, but became progressively linked by alongstrike growth and the development of new faults and fault segments. They thereby acquired the characteristics of Y-shears, dissecting the PSE-1-structures). By 2.4 cm of shear, segment 1 had become one unified fault array (**Figure 5D and 6D**), delineating a system of incipient push-ups or positive flower structures (*PSE-2-structures;* **Figures 8 and Figure 10, sections B1 and B3**, see also; Riedel 1929; Wilcox et al. 1973; Odonne & Vialon 1983; Dauteuil & Mart 1995; Dooley & Schreurs 2012).

The PSE-2-structures had amplitudes of 1 - 2 cm and wavelengths of 3 - 5 cm as measured on the surface with fault surfaces that steeped down-section, the deepest parts of the structures having cores of sand-layers deformed by open to tight folds. The folds had upright or slightly inclined axial planes, dipping up to 55°, mainly to the east. The structures also affected the shallowest layers down to 1-2 cm in the sequence, but the shallowest sequences were developed at a later stage of deformation and were characterized by simple gentle to open anticlines.

These structures were constrained to a zone of deformation directly above the trace of the basement fault, similar to that commonly seen along shear zones (e.g. Tchalenko 1971; Crowell 1974 a,b; Dooley & Schreurs 2012). This zone was 3-4 cm wide and remained stable throughout deformation stage 1 and was restricted to the close vicinity of the basement shear fault itself as also described from one-stage shear faults in Riedel box-type experiments (e.g. Tchalenko 1970; Naylor et al. 1986; Richard et al. 1991; Casas et al. 2001; Dauteuil & Mart 1998; Dooley & Schreurs 2012) and from nature as well (e.g. Wilcox et al. 1973; Harding 1974; Harding & Lowell 1979; Sylvester 1988: Woodcock & Schubert 1994; Mann 2007).

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A horse-tail-like fault array developed by ca. 3 cm of shear at the transitions between segments 1 and 2 (see also Cunningham & Mann 2007; Dooley & Schreurs 2012, their Figure 44) (**Figures 5B-D and 6B-D)**.

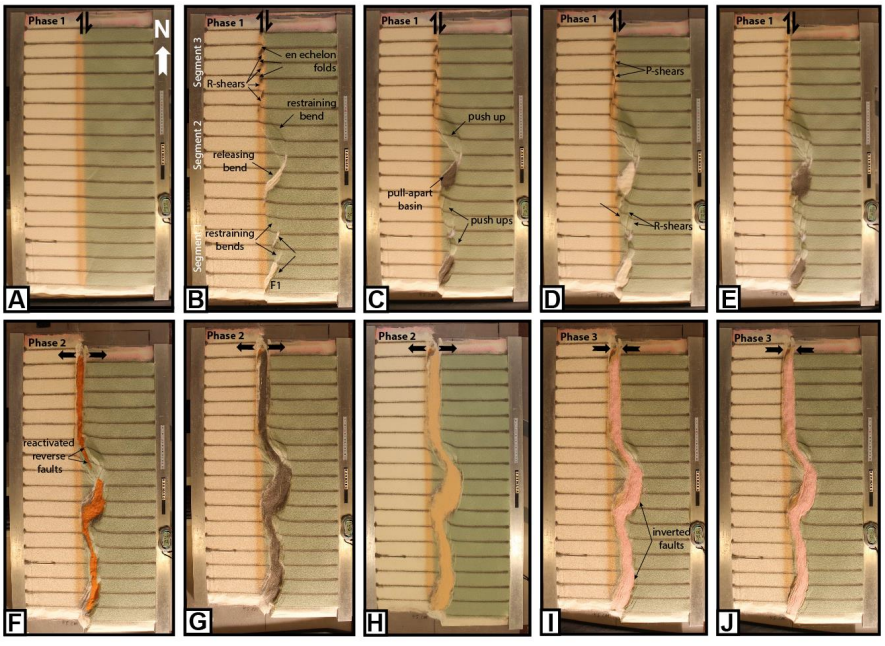

Figure 5: Sequential development of experiment BarMar6 by 0.5, 2.4, 3.5, 4.0 and 5.0cm of dextral shear (Steps A-E), orthogonal extension (steps F-H) and oblique contraction (steps I-J). The master fault strands are numbered in Figure 4, and the sequential development for each structural family is shown in Figure 7.

The structuring in *Segment 2;* was ruled by the crescent-shaped basement fault (VD) that generated a releasing bend along its southern and a restraining bend along its northern border (**Figure 11**). The first fault of fault array 3a-e in the southern part of Segment 2 was activated after c. 0.15 cm of bulk horizontal displacement (**Figure 7**). It was situated directly above the southernmost precut releasing bend, defining the margin of crescent-shaped incipient extensional strike-slip duplexes (in the context of Woodcock & Fischer, 1986, Woodcock & Schubert, 1994 and Twiss & Moores, 2007, p. 140-141). The developing basin got a spindle-shaped structure and developed into a basin with a lazy-S-shape (Cunningham & Mann 2007; Mann 2007).

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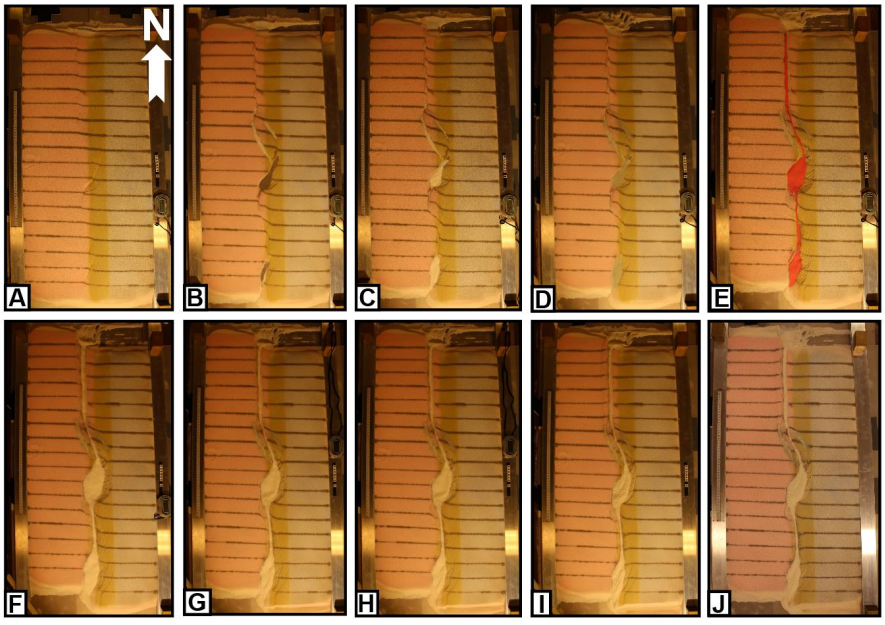

Figure 6: Sequential development of experiment BarMar8 by 0.5, 2.4, 3.5, 4.0 and 5.0cm of dextral shear (Steps A-E), oblique extension (steps F-H) and oblique contraction (steps I-J). The master fault strands are numbered in Figure 3, and the sequential development for each structural family is shown in Figure 7. Phases 2 and 3 involved oblique (3250) extension and contraction in this experiment.

The basin widened towards the east by stepwise footwall collapse, generating sequentially rotating crescent-shaped extensional fault blocks that became trapped as extensional horses in the footwall of the releasing bend (**Figure 11**). In the areas of the most pronounced extension the crestal part of the rotational fault blocks became elevated above the basin floor, generating ridges that influenced the basin floor topography and hence, the sedimentation. By continued sieving of sand layer on the top of these structures, forced folds (Hamblin 1965; Stearns 1978; Groshong 1989; Khalil & McClay 2016) were generated (**Figure 10A**). In the analysis we used the term *PSE-3-structures* for these features.

By a shear displacement of 0.55 cm additional curved splay faults were initiated from the northern tip of the master fault of fault 3f; **Figure 7**), delineating the northern margin of a rhombohedral pull-apart-basin (Mann et al. 1983; Mann 2007; Christie-Blick & Biddle 1985) and with a geometry that was indistinguishable from pull-apart basins or rhomb grabens affiliated with

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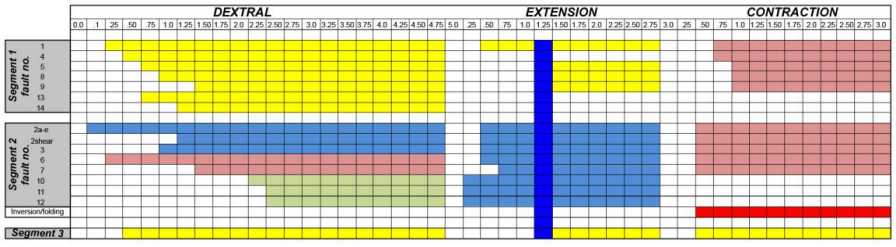

Figure 7: Summary of sequential activity in each master structural element (Figure 4) in Experiment BarMar6 (Figure 5). Type and amount of displacement is shown in two upper horizontal rows. The vertical blue bar indicates the stage at which full along-strike communication became established between marginal basins.

unbridged *en échelon* fault arrays (Crowell 1974 a,b; Aydin & Nur 1993). Although sand was filled into the subsiding basins to minimize the graben relief and to prevent gravitational collapse, the sub-basins that were initiated in the shear-stage were affected by internal cross-faults, and the initial basin units remained the deepest so that the buried internal basin topography maintained a high relief with several apparent depo-centers separated by intra-basinal platforms.

Systems of linked shear faults and PSE's became established in the central part with neutral shear that separate the releasing and restraining bends and development similarly to that seen for segment 3 (see below), but these structures were soon destroyed by the combined development of the northern and southern tips of the extensional and contractional shear duplexes (**Figure 10**).

The first structure to develop in the regime of the restraining bend (segment 2; was a top-to-the-southwest (antithetic) thrust fault at an angle of 145^0 with the regional trend of the basement border as defined by segments 1 and 3 (Fault 6). It became visible by 0.5 cm of displacement. The northern part of segment 2 became, however, dominated by a synthetic contractional top-to-the-northeast fault that was initiated by 0.85 cm of shear (Fault 7 **Figures 5 and 6**). Thus, faults 6 and 7 delineated a growing half-crescent-shaped 5-7-cm wide push-up structure (Aydin & Nur 1982; Mann et al. 1983) south of the restraining bend (**Figure 9**; *PSE-4-structures*). By continued shear these structures got the character of an antiformal stack.

Segment 3 defined a straight strand of neutral shear. Its development in the BarMar-experiments followed strictly that known from numerous published experiments (e.g. Tchalenko 1970; Wilcox et al. 1973; Harding 1974; Harding & Lowell 1979; Naylor et al. 1986; Sylvester 1988; Richard et al. 1991; Woodcock & Schubert 1994; Dauteuil &

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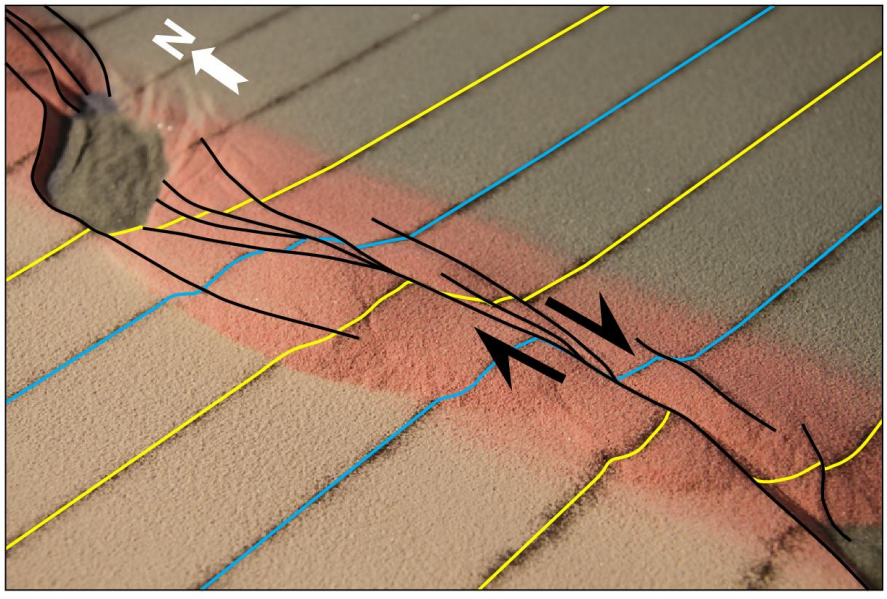

Figure 8: PSE-1 anticline-syncline pairs in segment 1 experiment BarMar6 in an oblique view. PSE-1 folds were constrained to the very fault zone and the fold axes (blue lines) and extended only 3-4 cm beyond the fault zone. PSE-2 structures (incipient push-ups and positive flower structures; yellow lines) were delineated by shear faults and completely cannibalized PSE-1 structures by continued shear. Yellow and blue lines show the rotation of the fold axial trace caused by dextral shearing of c. 1,5 cm. 25mm of dextral shear. By a displacement of 35mm the remains of the PSE-1 structure was completely obliterated. The distance between the markers (dark lines) is 5cm. Yellow arrow marks north-direction. White arrows indicate shear direction.

Mart 1998; Mann 2007; Casas et al. 2001; Dooley & Schreurs 2012). A train of Riedel-shears, occupying the full length of the segment, appeared simultaneously on the surface after a shear displacement of 0.5 cm, occupying a restricted zone with a width of 2-3 cm. The Riedel-shears dominated the continued structural development of Segment 3. Riedel'-shears were absent throughout the experiments, as should be expected for a sand-dominated sequence (Dooley & Schreurs 2012). P-shears developed by continued shear, creating linked rhombic structures delineated by the Riedel- and P-shears generating positive structural elements with NW-SE- and NNE-SSE-striking axes (see also Morgenstern & Tchalenko 1967), soon coalescing to form Y-shears. Transverse sections document that these structures were cored by push-up anticlines, positive half-flower structures. The segments with neutral shear would generate full-fledged positive flower structures in the advanced stages of shear (**Figures 5 and 6**). These were accompanied by the development of *en échelon* folds and flower

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structures as commonly reported from strike-slip faults in nature and in experiments. The width of the zone above the basal fault remained almost constant throughout the experiments, but was somewhat wider in experiments with thicker basal silicone polymer layers, similar to that commonly described from comparable experiments (e.g. Richard et al. 1991).

Deformation Phase 2: Extension

The late Cretaceous-Palaeocene dextral shear was followed by pure extension accompanying the opening along the Barents Shear Margin in the Oligocene. Our experiments utilized focused on the effects of oblique extension, acknowledging that plate tectonic reconstructions of the North Atlantic suggest an extension angle of 325° as the most likely (Gaina et al. 2009).

All strike-slip basins widened in the extensional stage, and most extensively so for the experiments with orthogonal extension. The widening of the basin enhanced the topography already generated in the shear-stage in the extensional strike-slip duplex in segment 2 (PSE-3-structures). In the earliest extensional stage the strike-slip basin in segment 2 dominated the basin configuration, but by continued extension the linear segments and the minor pull-apart basins in segments 1 and 2 started to open and became interlinked, subsequently generating a linked basin system that paralleled the entire shear margin (**Figures 5F-G, 6F-G**).

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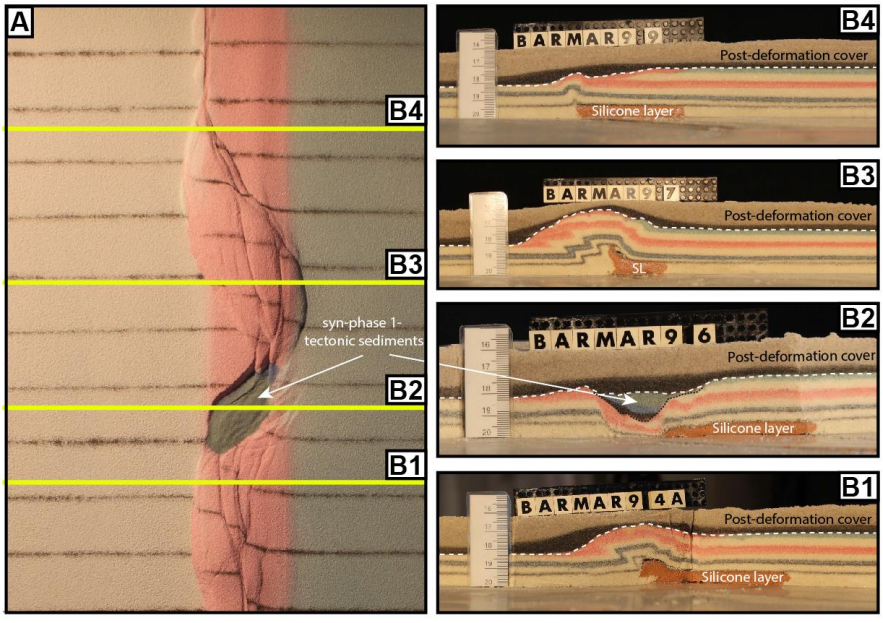

Figure 9: Cross-sections through PSE-2-related structures. A) Folded core of incipient push-up/positive flower structure in segment 1, experiment BarMar6. The fold structure is completely enveloped of shear faults that have a twisted along-strike geometry. Note that the eastern margin of the structure developed into a negative structure at a late stage in the development (filled by black-pink sand sequence) and that the silicone putty sequence (basal pink sequence) was entirely isolated in the footwall. B) Similar structure in experiment BarMar8. The weak silicone putty layer here bridged the high-strain zone and focused folding that propagated into the sand layers (blue). The folds in upper (pink layers) were associated with the contractional stage, because they contributed to a surface relief filled in by red-black-sand sequence that was sieved into the margin during the contractional stage. C) Contraction associated with "crocodile structure" in the footwall of the main fault in segment 1, experiment BarMar8. Note disharmonic folding with contrasting fold geometries in hanging wall and footwall and at different stratigraphic levels in the footwall, indicating shifting stress situation in time and space in the experiment.D) Transitional fault strand between to more strongly sheared fault segments (experiment BarMar9).

The orthogonal extension-phase following dextral strike-slip reactivated and very quickly linked several of the master faults that were established in deformation phase 1 (**Figures 5A and 6A**) already by an extension of 0,25 – 0,50 cm. This included the southern fault margin, the push-up and the splay faults defining a crestal collapse graben of the push-up (Faults 6, 11 and 12; **Figure 4**). All three segments were reactivated in extension by c. 1.25 cm of orthogonal stretching (**Figure 7**). During the first cm of extension each basin remained an isolated unit, but after 1 cm of extension

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all basins became linked, thus forming one unified elongate extensional basin (marked by the vertical dark blue line in **Figure 7**) and mainly following the PDZ as it was cut in the basal templates. Among the faults that were inactive and remained so throughout the extension phase were the antithetic contractional fault delineating the push-ups in segment 2 towards the south (Fault 6; **Figure 4**). The Y-shear in Segment 3 was reactivated as a straight, continuous extensional fault in Stage 2. Total extension in Phase 3 was 5 cm.

Deformation Phase 3: contraction

In our experiments the extension stage was followed by orthogonal or oblique contraction (parallel to the direction of extension as applied for each experiment). The experiments were terminated before the full closure of the basin system, i.e. the extension vector > contraction vector. A part of the early-stage contraction was accommodated along new faults. It was more common, however, that faults that had been generated in the strike-slip and extensional stages became reactivated and rotated. This was particularly the case for the master faults., as seen by continued or accelerated subsidence. The dominant structures affiliated with the contractional stage was still new folds with traces oriented orthogonal to the shortening direction and sub-parallel to the preexisting master fault systems that defined the margin and basin margins (**Figure 12**). Also some deep fold sets that had been generated during the strike-slip phase and seen as domal surface features became reactivated, causing renewed growth of surface structures (see **Figure 10** and explanation in figure caption). These folds were generally up-right cylindrical buckle folds in the initial contractional and with very large trace length: amplitude-ratio (*SPE-5-structures*). Some intra-basinal folds, however, defined fold arrays that diagonally crossed the basins. Particularly the folds situated along the basin margins developed into fault propagation-folds above low-angle thrust planes. Such faults aligning the western basin margins could have an antithetic attitude relative to the direction of contraction.

During the contractional phase the margin-parallel, linked basin system started immediately to narrow and several fault strands became inverted. The basin-closure was a continuous process until the end of the experiment by 3 cm of contraction. The contraction was initiated as a proxy for an ESE-directed ridge-push stage. The first effect of this deformation stage was heralded by uplift of the margin of the established

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shear zone that that had developed into a rift during deformation stage 2. This was followed by the reactivation and inversion of some master faults (e.g. fault a2; e.g. **Figure 4**) and thereafter by the development of a new set of low-angle top-to-the-ESE contractional faults. These faults displayed a sequential development, (fault family 1; **Figure 4**) and were associated with folding of the strata in the rift structure, probably reflecting foreland-directed in-sequence thrusting.

Discussion

The break-up and subsequent opening of the Norwegian-Greenland Sea was a multi-stage event (**Figure 13**) that imposed shifting stress relation on the already geometrically complex Barents Shear Margin. The incipient stages occurred in the late Cretaceous – early Palaoecene (e.g. Eldholm et al 1987; Vågnes 1997; Myhre & Eldholm 1988; Gabrielsen et al. 1990; Gudlaugsson & Faleide. 1994; Knutsen & Larsen 1997; Ryseth et al. 2003; Faleide at al. 1993; 2008; Reemst et al. 1994; Bergh & Grogan 2003; Kristensen et al. 2017), and the development included extensive volcanism (Eldholm et al. 1989; Saunders et al. 1997; Planke et al. 1999; Ganerød et al. 2010; Horni et al. 2017). Opening accelerated and was accompanied by extensive marine sedimentation in the Eocene and changed into a passive margin setting from the earliest Oligocene. The spreading stage was likely associated with ridge-push (e.g. Doré & Lundin 1996; Vågnes et al. 1998; Pascal & Gabrielsen 2001), plate reorganization (Talwani & Eldholm 1977, Gaina et al. 2009) or other far-field stresses (Doré & Lundin 1996; Lundin & Doré 1997; Doré et al. 1999; Lundin et al. 2013). Faults, and fold arrays associated with shear and tectonic inversion as well as elements of subsidence/elevation are obviously prominent for the deduction of the structural history in such systems (e.g. Cloos 1928, 1955; Riedel 1929; Campbell 1953; Tchalenko 1970; Wilcox et al. 1973; Dauteuil & Mart 1998; Odonne & Vialon 1983; Richard et al. 1991; Richard & Kranz 1991; Dooley & McClay 1997; Basile & Brun 1999; Mitra & Paul 2011; Dooley & Schreurs 2012; Kristensen et al. 2017). Therefore, scaled experiments were designed to illuminate these complexities of the Barents Shear Margin. The experiments utilized three main segments that correspond to the Senja Fracture Zone (segment 1), the Vestbakken Volcanic Province (segment 2) and the Hornsund Fault

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Zone (segment 3). A series of structural families developed during the experiments, most of which correspond to structural elements found along the Barents Shear Margin. Segment 1 in the experiments (which correponds to the Senja Fracture Zone) was dominated by neutral dextral shear, although subordinate jogs in the (pre-cut) fault provided minor sub-segments with mainly releasing and subordinate restraining bends. PSE-1-folds, that developed at an incipient stage were immediately paralleled by two sets of normal faults with opposite throw in the releasing bend areas (e.g. fault 2 **Figure 4**) so that the two faults constrained a crescent- or spindle-shaped incipient extensional shear duplex became evident (**Figures 5B and 6B**; see also Mann et al. 1983; Christie-Blick & Biddle 1985; Mann 2007; Dooley & Schreurs 2012). The most prominent of these structures corresponds to the position of the Sørvestsnaget Basin (**Figure 1B**).

Structures generated at an early stage in a developing, multistage systems that involve shear, extension and contraction soon became overprinted and canabalized by younger structures with axes parallel to the main shear fault (Y-shears). The strike-slip stage of the experiments is comparable to the experiments in series “e” and “f” of Mitra & Paul (2011). It is particularly emphasized that SPE-1 and SPE-2-structures were confined to the area just above the basal master fault (VD) and its immediate vicinity. Although careful search for positive early (PSE-1) in the reflection seismic data was conducted, no remains of such structures were detected.

During the oblique extension stage segment 1 of experiments BarMar7-9 were characterized by oblique opening. The basin subsidence was focused in the minor pull-apart basins, which soon became linked along the regional N-S-striking basin axis. Remains of several such basin centers, of which the Sørvestsnaget Basin (Knutsen & Larsen 1997; Kristiansen et al. 2017) is the largest, are preserved and found in seismic data (**Figure 1b**). During the experiments a continuous basin system was developed in the hangingwall side of the master fault, but it is not likely that such a superior basin system ever existed along the Barents Shear Margin.

In the subsequent inversion stage, fold trains with axial traces parallel (PSE-5-folds) to the basin axis and the master faults characterized segment 1. Remnants of such folds are locally preserved in the thickest sedimentary sequences affiliated with the Senja Shear Margin.

Segment 2, which was underlain by a crescent-shaped discontinuity corresponds to theVestbakken Volcanic Province and the southern extension of the Knølegga Fault

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Complex that is a branch of the southern part of the Hornsund Fault Zone (**Figure 1b**). The part of the Vestbakken Volcanic Province that was the subject of structural analysis by Giennenas (2018) corresponds to the southern part of segment 2 in the present experiments. It is dominated by interfering NNW-SSE- and NE-SW striking fold- and fault systems in the central part of the basis, whereas N-S-structures are more common along its eastern margin (**Figure 12A**) (Jebsen & Faleide 1998; Giennenas 2018).

Intra-basinal platforms and complex internal configurations seen in the BarMar-experiments are common in strike-slip basins (e.g. Dooley & McClay 1997; Dooley & Schreurs 2012) and are consistent with the structural configuration with intra-basinal depo-centers within the Vestbakken Volcanic province and also in the Sørvestsnaget Basin (Knutsen & Larsen 1997; Jebsen & Faleide 1998; **Figure 13**).

The positive structural elements that prevail in *segment 3* are similar to PSE-1 and PSE-2-structres described for segment 1. The structures affiliated with segment 3 in the BarMar-experiments correspond well to that seen in the reflection seismic sections along parts of the Spitsbergen and the Senja shear margins (Myhre et al. 1982). Thus, the structuring in the segment 3 in the BarMar-experiments followed strictly the pattern well established for neutral shear in that an array of NW-SE-striking *en echelon* wrench folds (termed PSE-1-structures in the description above; see Cloos 1928; Riedel 1929; Tchalenko 1970; Wilcox et al. 1973) first became visible and the development of Riedel- and P-shears. (R'-shears were subdued as expected for sand-dominated sequences (Dooley & Schreurs 2012). Continued shear followed by collapse and interaction between Riedel and P-shears and the subsequent development of Y-shears initiated push-up- and flower-structure with N-S-axes (PSE-2) structures that were expressed as non-cylindrical (double-plunging) anticlines on the surface (e.g. Tchalenko 1970; Naylor et al. 1986). Structures similar to the PSE-2-structures that were initiated in the present experiments have previously been reported from similar experiments with viscous basal layers covered by sand (e.g. Richard et al. 1991; Dauteuil & Mart 1998), and may have contributed to the more complex fold systems along the Knølegga Fault Complex.

The Knølegga Fault Complex occupies a km-wide zone. The master fault strand is paralleled by faults with significant normal throws on its hanging wall side and these are considered to be strands belonging to the larger Knølegga Fault Complex (EBF; Eastern Boundary Fault; Giannenas 2018; **Figure 12A**). The EBF zone is a top-west normal fault with maximum throw of nearly 2000 ms (3000 meters). It can be followed

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along its strike for more than 60 km and seems to die out by horse-tailing at its tip-points. The vicinity of the master faults of the Knølegga Fault Complex locally display isolated elongate positive structures constrained by steeply dipping faults. These structures sometimes display internal reflection patterns that seem exotic or suspect in comparison to the surrounding sequences. Some of these structures resemble positive flower structures or push-ups or define narrow anticlines. They are found in both the footwall and hanging wall of the border faults and strike parallel to those and the axes of these structures parallel the master faults. The traces of such structures can be followed over shorter distances than the master faults, and do not occur in the central parts of the Vestbakken Volcanic Province. We speculate that these are rare fragments of dismembered EPS-2-type structures.

Due to the right-stepping geometry during dextral shear in segment 2, the southern and northern parts were in the releasing and restraining bend positions,

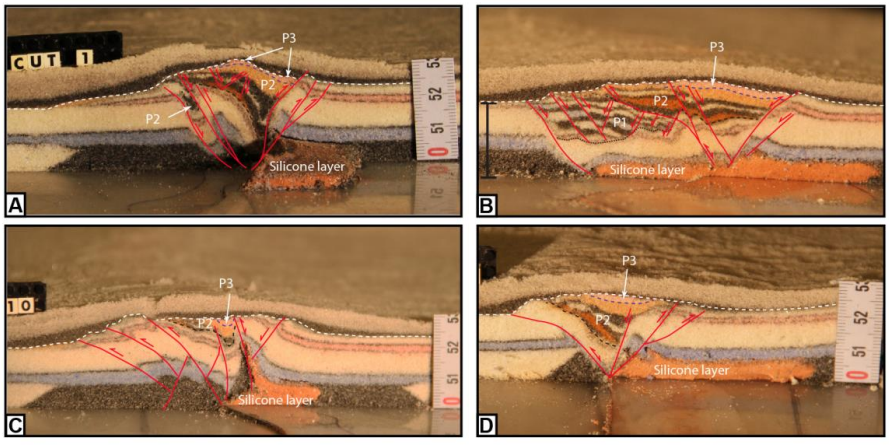

Figure 10: A) contrasting structural styles along the master fault system in segment 2 in map view and (B) cross sections of experiment BarMar9. SL denotes silicone layer, the stippled line the boundary between pre-and syn-deformation layers and the white dashed line the boundary with the post-deformation layers.

respectively (e.g. Christie-Blick & Biddle 1985). Hence, the southern part of segment 2 was subject to oblique extension, subsidence and basin formation when the northern part was subject to oblique contraction, shortening and uplift. The southern segment expanded to the east and northeast by footwall collapse and activation of rotating fault blocks that contributed to a basin floor topography that affected the pattern of sediment accumulation (**Figure 9A, B**). The crests of the rotating fault blocks are termed PSE-3-

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structures above, and such eroded fault block crests are defining the footwalls of major faults in the Vestbakken Volcanic Province, providing space for sediment accumulation in the footwalls. The area that was affected by the basin formation in the extensional shear duplex stage seems to have remained the deepest part of the Vestbakken Volcanic Province, whereas the part formed in basin widening by sequential footwall collapse created a shallower sub-platform (*sensu* Gabrielsen 1986) (**Figure 11**). It is expected that (regional) basin and (local) fault block subsidence became accelerated during phase 2 (extension), and more so in the orthogonal extension experiments (BarMar 6) than in the experiments with oblique extension (BarMar 8), but due to stabilization of basins by infilling of sand, this was not documented. The widening occurred mainly by fault-controlled collapse of the footwalls, and dominantly along the master faults that corresponded to the Knølegga Fault Complex, but also new intra-basinal cross-faults that were initiated in the shear stage (see above) became reactivated, contributing to the complexity of the basin topography.

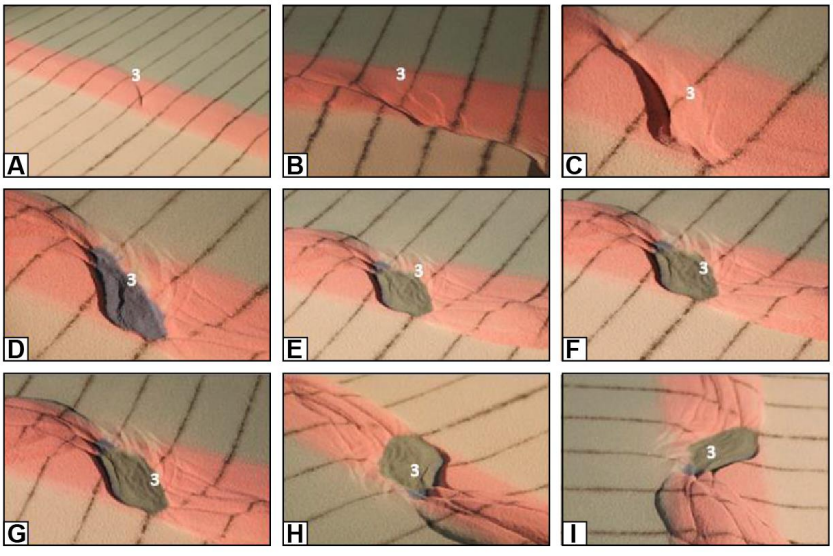

Figure 11: Nine stages in the development of the extensional shear duplex system above the releasing bend in experiment BarMar9. The master faults that developed at an incipient stage (e. Fault 3 that constrained the eastern margin of the extensional shear duplex) remained stable and continued to be active throughout the experiment (Figure 7), but became overstepped by faults in its footwall that became the basin contraction faults at the later stages H and I. Note that the developing basement was stabilized by infilling of gray sand during this part of the experiment. Note that Fault 3 remained active and broke through the basin infill also after the basin infill overstepped the original basin margin. The distance between the markers (dark lines) is 5cm. Yellow arrow marks north-direction.

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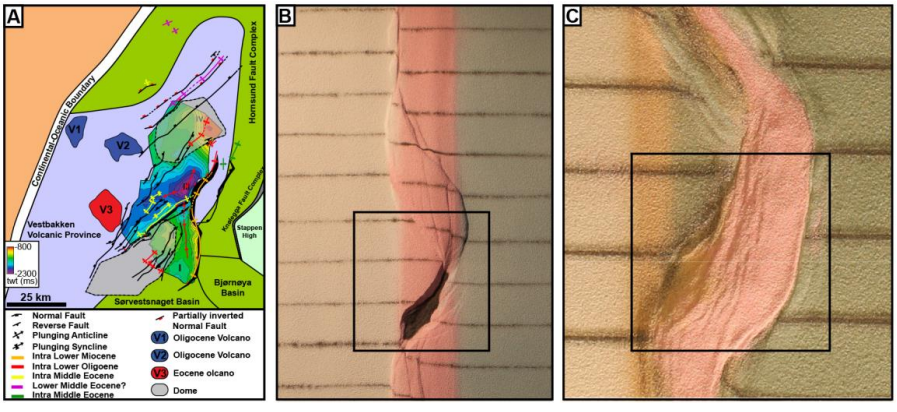
884 Referring the reflection seismic data from the Barents Shear Margin, it is not likely that
885 a stage was reached where all basins along the margin became fully linked, although
886 sedimentary communication along the margin is likely.
887 The contraction (phase 3) clearly reactivated normal faults, probably causing focusing
888 of hanging wall strain and folding, rotation of fault blocks and steepening of faults. This
889 means that both intra-basinal and marginal faults in the Vestbakken Volcanic Province
890 can have suffered late steepening. Contraction expressed as fold systems with fold axes
891 paralleling the basin margins development seems to correspond very well to the
892 observed structural configuration of the Vestbakken Volcanic Province. Here
893 pronounced tectonic inversion is focused along the N-S-striking basin margins and
894 along some NE-SW-striking faults in the central parts of the basin. Pronounced
895 shortening also occurred inside individual reactivated fault blocks either by bulging of
896 the entire sedimentary sequence or as trains of folds (**Figure 12**).
897
898 The restraining bend configuration in the northern part of segment 2 was characterized
899 by increasing contraction across strike-slip fault strands that splayed out to the
900 northwest from the central part of segment 2 in an early stage of dextral shear.. This
901 deformation was terminated by the end of phase 1 by



902
903 Figure 12: PSE-5-folds generated during phase 3-inversion, experiment BarMar8. Note
904 that fold axes mainly parallel the basin rims, but that they deviate from that in the central
905 parts of the basins in some cases. Note that the folds are best developed in segment 2,
906 which accumulated extension in the combined shear and extension stages.
907
908 stacking of oblique contraction faults (PSE-4-structures), defining and antiformal
909 stack-like structure. This type of deformation falls outside the main area, but to the

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north this type of oblique shortening during the Eocene (phase 1) was accommodated by regional-scale strain partitioning (Leever et al. 2011a,b).

The Vestbakken Volcanic Province is characterized by extensive regional shortening. Onset of this event of inversion/contraction is dated to early Miocene (Jebsen & Faleide 1998, Giennenas 2018) and this deformation included two main structural fold styles. The first includes upright to steeply inclined closed to open anticlines that are typically present in the hanging wall of master faults. These folds typically have wavelengths in the order of 2.5 to 4.5 kilometers, and amplitudes of several hundred meters. Most commonly they appear with head-on snakehead-structures and are interpreted as buckle folds, albeit a component shear may occur in the areas of the most intense deformation, giving a snake-head-type geometry. The second style includes gentle to open anticline-syncline pairs with upright or steep to inclined axial planes open anticlines-synclines with wavelengths in the order of 5 to 7 kilometers and amplitudes of several tens of meters to several hundred meters. We associate those with the PSE-4-type structures as defined in the BarMar-experiments, where folds of the former type are situated in positions here sedimentary sequences have been pushed against buttresses provided by master faults along the basin margins, whereas the latter type was developed as fold trains in the interior basins, where buttressing against larger fault walls was uncommon. Also this pattern fits well with the development and geometry seen in the BarMar-experiments, where folding started in the central parts of the closing basins before folding of the marginal parts of the basin. In the closing stage the folding and inversion of master faults remained focused along the basin margins.

The experiments clearly demonstrated that contraction by buckle folding was the main shortening mechanism of the margin-parallel basin system generated in phase 2 (orthogonal or oblique extension) in all segments. In the Vestbakken Volcanic Province segments of the Knølegga Fault Complex, the EBF and the major intra-basinal faults contain clear evidence for tectonic inversion, whereas this is less pronounced in others. The hanging wall of the EBF is partly affected by fish-hook-type inversion anticlines (Ramsey & Huber 1987; Griera et al. 2018) (**Figure 2D, E**), or isolated hanging wall anticlines or pairs or trains of synclines and anticlines (e.g.; Roberts 1989; Coward et al. 1991; Cartwright 1989; Mitra 1993; Uliana et al. 1995; Beauchamp et al. 1996; Gabrielsen et al. 1997; Henk & Nemcok 2008), the fold style and associated faults probably being influenced by the orientation and steepness of the pre-inversion fault (Williams et al. 1989; Cooper et al. 1989; Cooper & Warren 2010).

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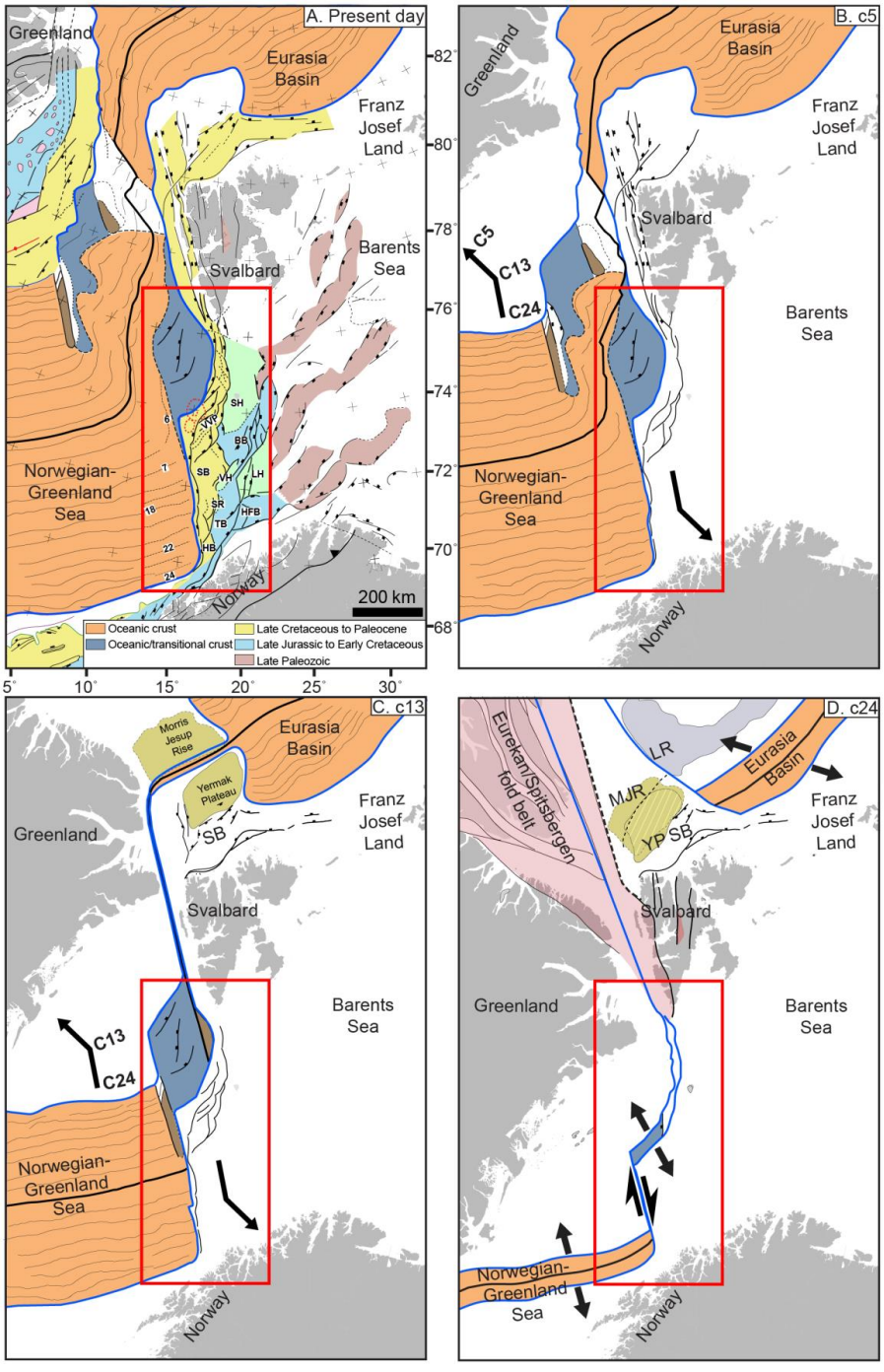

Figure 13: Main stages in opening of the North Atlantic.

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Some structures of this type can still be followed for many kilometers having consistent geometry and attitude. These structures have not been much modified by reactivation and are invariably found in the proximal parts footwalls of master faults, suggesting that these are inversion structures correlate to EPS-type 5-structures in the experiments developed in areas of focused contraction along pre-existing fault scarps during Oligocene inversion.

Trains of folds with smaller amplitudes and higher frequency are sometimes found in fault blocks in the central part of the Vestbakken Volcanic Province (**Figure 12F**). Although these structures are not dateable my seismic stratigraphical methods (on-lap configurations etc.) we regard these fold strains to be correlatable with the tight folds generated in the inversion stage in the experiments (EPS-5-structures) and that they are contemporaneous with the EPS-type5-structures.

Segment 1 in the experiments that corresponds to the Senja Shear Margin displays a structural pattern that is a blend done between configurations done in segments 1 and 2, and the general conclusions drawn above are valid for this part of the shear margin.

Summary and conclusions

The Barents Shear Margin is a challenging target for structural analysis both because it represents a geometrically complex structural system with a multistage history, but also because high-quality (3D) reflection seismic data are limited and many structures and sedimentary systems generated in the earlier tectonothermal stages have been overprinted and obliterated by younger events. This makes analogue experiments very useful in the analysis, since they offer a template for what kind of structural elements can be expected. By constraining the experimental model according to the outline of the margin geometry and imposing a dynamic stress model in harmony according to the state-of-the-art knowledge about the regional tectono-sedimentological development, we were able to interpret the observations done in reflection seismic data in a new light.

Our observations confirmed that the main segments of the Barents Shear Margin, albeit undergoing the same reginal stress regime, display contrasting structural configurations

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The deformation in segment 2 in the BarMar-experiments, was determined by releasing and restraining bends in the southern and northern parts, respectively. Thus, the southern part, corresponding to the Vestbakken Vocanic Province, was dominated by the development of a regional-scale extensional shear duplex as defined by Woodcock & Fischer (1983) and Twiss & Moores (2007). By continued shear the basin developed into a full-fledged pull-apart basin or rhomb graben (Crowell 1974; Aydin & Nur 1982) in which rotating fault blocks were trapped. The pull-apart-basin became the nucleus for greater basin systems to develop in the following phase of extensional and also provided the space for folds to develop in the contractional phase.

We conclude that fault- and fold systems found in the realm of the Vestbakken Volcanic Province are in accordance with a three-stage development that includes dextral shear, (oblique) extension and contraction along a shear margin with composite geometry. Folds with NE-SW-trending fold axes that are dominant in wider area of the Vestbakken Volcanic Province and are dominated by folds in the hanging walls of (older) normal faults, sometimes characterized by narrow, snake-head- or harpoon-type structures that are typical for tectonic inversion (Cooper et al. 1989; Coward 1994; Allmendinger 1998; Yameda & McClay 2004; Pace & Calamitra 2014) typical of inverted faults.

Comparing seismic mapping and analogue experiments it is evident that a main challenge in analyzing the structural pattern in shear margins of complex geometry and multiple reactivation is the low potential for preservation of structures that were generated in the earliest stages of the development.

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Code/Data availability

The seismic data that support the findings of this study are available from NPD and TGS. Restrictions apply to the availability of these data, which were used under license for this study.

Author contribution

R.H.Gabrielsen: Contributions to outline, design and performance of experiments. First writing and revisions of manuscript. First drafts of figures.

P.A.Giennenas: Seismic interpretation in the Vestbakken Volcanic Province. Identification and description of fold families.

D.Sokoutis: Main responsibility for set-up, performance and handling of experiments. Revisions of manuscript.

E.Willigshofer: Performance and handling of experiments. Revisions of manuscript. Design and revisions of figure material.

M.Hassaan: Background seismic interpretation. Discussions and revisions of manuscript. Design and revisions of figure material.

J.I.Faleide: Regional interpretations and design of experiments. Participation in performance and interpretations of experiments. Revisions of manuscript, design and revisions of figure material.

Competing interests

At least one of the (co-)authors (Ernst Willingshofer) is a guest member of the editorial board of Solid Earth for special issue (Analogue modelling of basin inversion). To the best of our knowledge, no other conflict of interest, financial or other, exists.

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