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Evolution of a major segmented normal fault during multiphase rifting: The origin of plan-view zigzag geometry

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This case study addresses fault reactivation and linkage between distinct extensional episodes with variable stretching direction. Using 2-D and 3-D seismic reflection data we demonstrate how the Vesterdjupet Fault Zone, one of the basin-bounding normal fault zones of the Lofoten margin (north Norway), evolved over c. 150 Myr as part of the North Atlantic rift. This fault zone is composed of NNE-SSW- and NE-SW-striking segments that exhibit a zigzag geometry. The structure formed during Late Jurassic and Early Cretaceous rifting from selective reactivation and linkage of Triassic faults. A rotation of the overall stress field has previously been invoked to have taken place between the Triassic and Jurassic rift episodes along the Lofoten margin. A comparison to recent physical analogue models of non-coaxial extension reveals that this suggested change in least principal stress for the Lofoten margin may best explain the zigzag-style linkage of the Triassic faults, although alternative models cannot be ruled out. This study underlines the prediction from physical models that the location and orientation of early phase normal faults can play a pivotal role in the evolution of subsequent faults systems in multi-rift systems.

1. Introduction

The evolution of normal faults (initiation, propagation, linkage) is traditionally described as the progressive incidental coalescence of growing fault segments that started off as geometrically and kinematically independent structures. This process has been documented for both outcrop and seismic studies (e.g. Peacock and Sanderson, 1991; Cartwright et al., 1996; McLeod et al., 2000; Young et al., 2001) as well as modeling studies (e.g. Scholz et al., 1993; Crider and Pollard, 1998; Cowie et al., 2000). Linkage through propagation of initially unrelated faults has recently been referred to as the 'isolated fault model' (Walsh et al., 2003). The alternative 'coherent fault model' describes how a soft-linked fault array can form as a system that is kinematically linked since initiation (Morley et al., 1999; Walsh et al., 2002, 2003). The coherent fault model can explain how a pre-existing, large fault at depth can be reactivated in such a way that, at surface, new faults develop that are soft-linked (e.g. Giba et al., 2012; Jackson and Rotevatn, 2013).

Propagation and linkage of faults involves the destruction of relay ramps. Such overlap zones between normal faults are formed and obliterated throughout the formation of a normal fault zone (Peacock and Sanderson, 1991; Childs et al., 1995); this is a continuous process that occurs without a change in the overall extension vector, and regardless of whether the fault system forms via the isolated or the coherent fault model. Physical models simulating uniform extension typically yield mostly parallel structures with minor lateral steps (Keep and McClay, 1997; Henza et al., 2011). The parallel geometries of faults growing under uniform extension was observed in nature by Acocella et al. (2000), who stated that in their study area, the combined length of parallel normal faults would have to be less than fourteen times their strike-normal separation in order for the faults to interact.

In contrast, physical models simulating the effects of various degrees of non-coaxial extension revealed that, after a change in the direction of extension, widely spaced first phase faults would link up to produce fault systems with strong zigzag or cross-cutting plan-view geometries (Henza et al., 2011). While the pivotal role of (oblique) reactivation has now been investigated extensively in physical models (see also Dubois et al., 2002), natural examples from the geological record are rare. This mode of linking fault

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segments may explain some types of zigzag fault patterns as commonly seen in rift systems (e.g. Freund and Merzer, 1976; Lepvrier et al., 2002; Jackson et al., 2002; Morley et al., 2004, 2007; Bergh et al., 2007; Whipp et al., 2014).

This study investigates the c. 100 km long Mesozoic Vesterdjupet Fault Zone (VFZ; Blystad et al., 1995) which forms the main border fault to the North Træna Basin. The spatio-temporal relationship between its constituent segments is presently not well known. Bergh et al. (2007) argue that differently striking fault populations of the Lofoten margin reflect distinct rift pulses (see also: Eig and Bergh, 2011; Færseth, 2012). More specifically, they suggest that the NNE-SSW-striking segments of the VFZ predate NE-SW-striking segments, with the latter forming transfer faults linking the former. In contrast, Wilson et al. (2006) suggest that the differently striking segments of Mesozoic normal faults of the Lofoten margin could have formed simultaneously as conjugate sets under a uniform stress field, locally perturbed by an inherited Caledonian basement grain or a transfer zone.

We have mapped the hanging wall to the VFZ in detail using an extensive database of old, reprocessed as well as recently acquired 2-D and 3-D seismic reflection surveys. The VFZ and its constituent parts have been reactivated repeatedly; the tectonic style of the Triassic and Jurassic rift episodes has therefore been overprinted by Cretaceous rifting. Specific structures within its hanging wall, on the other hand, record only these earlier rift episodes, after which activity on them ceased. We assume that these abandoned hanging wall faults and the precursors to the VFZ evolved similarly prior to Cretaceous rifting. The abandoned hanging wall faults are therefore used as proxies for the evolution of the proto-VFZ during the Triassic and Jurassic rift episodes.

Our results show that each subsequent Mesozoic rift episode is associated with reactivation of structures from the foregoing episode, as well as inception of new faults. We thus support the model of Bergh et al. (2007), and demonstrate how the VFZ, with its characteristic zigzag plan-view geometry, formed by reactivation and linkage of Triassic faults during subsequent rift events in the Late Jurassic and Early Cretaceous. By comparing the results of this case study to recent physical models simulating coaxial- and non-coaxial extension, we aim to carry insights from such analogues to the understanding of natural rifts. We present several scenarios for the origin of zigzag geometries of segmented normal faults and discuss alternative models for fault growth and the influence of a change in extension direction.

2. Geological setting

2.1. The Lofoten segment of the Norwegian passive continental margin

The Norwegian passive continental margin forms part of the eastern side of the greater North Atlantic, which evolved during Palaeozoic–Mesozoic continental rifting and eventual breakup in early Cenozoic times. This complex tectonic history resulted from divergent plate motions between Eurasia and Laurentia during breakup of Pangea (Doré, 1992), which in the North Atlantic was largely accomplished by a rift along the Caledonian suture (Doré, 1992; Torsvik and Cocks, 2003).

The Lofoten-Vesterålen margin segment is bordered to the southwest and northeast by the continental continuations of oceanic transform zones (Mosar et al., 2002). To the southwest, the Bivrost Lineament separates it from the greater Vøring Basin and the Trøndelag platform, whereas to the northeast the margin segment is bordered by the Senja Fracture Zone, which forms part of the western Barents Sea transform margin (Doré et al., 1997; Olesen et al., 2002). This study focuses on the shelfal area west of the Lofoten Islands (Fig. 1; herein referred to as the Lofoten margin).

The contractional phase of the Caledonian Orogeny was replaced by a phase of orogenic collapse and exhumation of thickened crust in Devonian times (Andersen et al., 1991; Fossen, 2000), which lasted until the Permian in the Lofoten area (Hames and Andresen, 1996), at which time it was facilitated by the development of a metamorphic core complex (Hames and Andresen, 1996; Steltenpohl et al., 2004; Henstra and Rotevatn, 2014). Subsequently the area between Greenland and Norway experienced recurring episodes of rifting that alternated with periods of relative tectonic quiescence or uplift (Lundin and Doré, 1997; Brekke, 2000; Faleide et al., 2008).

The late Permian to earliest Cretaceous interval of the Lofoten margin is subdivided into two main rift episodes (Hansen et al., 1992, 2012; Færseth, 2012), very similar to the Northern North Sea and Mid Norwegian margin: i) a latest Permian to Early Triassic episode and ii) a Middle Jurassic to earliest Cretaceous episode. In the Lofoten Margin, another rift event occurred towards the end of the Early Cretaceous (Hansen et al., 1992; Blystad et al., 1995; Løseth, H., Tveten, 1996; Doré et al., 1999; Tsikalas et al., 2001).

The initial framework of Hansen et al. (1992), in which two distinct periods of rifting are recognized in the Early Cretaceous, has been adopted by several more recent studies (Koch and Heum, 1995; Brekke, 2000; Tsikalas et al., 2001; Surlyk, 2003). However, two alternative schools of thought exist; following Doré (1992), Lundin and Doré (1997), Doré et al. (1999) and Hansen et al. (2012), the Early Cretaceous is characterised by a period of rifting that began in the Valanginian. Rifting cessation is associated with a middle Cenomanian erosional event. Færseth (2012) on the other hand argues that the Lower Cretaceous itself resembles post-rift basin-fill, with fine-grained marine sediments infilling sediment-starved, inactive half-grabens inherited after Late Jurassic rifting. Our results indicate that the nature of the lower part of the Lower Cretaceous fits the model of Færseth (2012), but that the upper part of the Lower Cretaceous records an important rift episode during which Triassic and Jurassic faults were reactivated and linked up to form large, segmented fault zones.

A final rift episode occurred in Campanian to Palaeogene across the Norwegian continental shelf (Skogseid et al., 2000; Færseth and Lien, 2002; Gernigon et al., 2003). In the Lofoten margin widespread fault block rotation resulted in reinvigorated activity along the major basin bounding fault systems that govern the half-graben architecture of the Lofoten margin (Tsikalas et al., 2001; Færseth, 2012; Hansen et al., 2012).

2.2. Evolution of the regional stress regime during the Mesozoic

The Permo-Triassic rift episode of the northern North Atlantic is characterised by E–W directed extension (Mosar et al., 2002; Coward et al., 2003; Faleide et al., 2010). For the Lofoten margin specifically, NNE-trending structures of this age have been documented both onshore (Steltenpohl et al., 2004; Wilson et al., 2006) and offshore (Hansen et al., 1992, 2012; Færseth, 2012).

For the Lofoten margin a change in extension direction has been invoked for the Late Jurassic to Early Cretaceous rift episode based on the development of NE-SW- to E-W-striking faults in addition to continued activity of NNE-SSW-striking ones (Tsikalas et al., 2001; Bergh et al., 2007), similar to other areas of the Norwegian continental shelf (Færseth et al., 1997; Clifton et al., 2000). This suggests that since the Permo-Triassic rift episode, the extensional stress field vector had rotated c. 30–50° clockwise. This stress rotation was also invoked by Faleide et al. (2008), who emphasise its regional, NE Atlantic-Arctic nature. Alternatively, Færseth (2012) and Hansen et al. (2012) interpret inception of NE-SW- to E-W-