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Pre-existing normal faults have limited control on the rift geometry of the northern North Sea

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ABSTRACT

Many rifts develop in response to multiphase extension with numerical and physical models suggesting that reactivation of first-phase normal faults and rift-related variations in bulk crustal rheology control the evolution and final geometry of subsequent rifts. However, many natural multiphase rifts are deeply buried and thus poorly exposed in the field and poorly imaged in seismic reflection data, making it difficult to test these models. Here we integrate recent 3D seismic reflection and borehole data across the entire East Shetland Basin, northern North Sea, to constrain the long-term, regional development of this multiphase rift. We document the following key stages of basin development: (i) pre-Triassic to earliest Triassic development of multiple sub-basins controlled by widely distributed, NNW- to NE-trending, east- and west-dipping faults; (ii) Triassic activity on a single major, NE-trending, west-dipping fault located near the basins western margin, and formation of a large half-graben; and (iii) Jurassic development of a large, E-dipping, N- to NE-trending half-graben near the eastern margin of the basin, which was associated with rift narrowing and strain focusing in the Viking Graben. In contrast to previous studies, which argue for two discrete periods of rifting during the Permian–Triassic and Late Jurassic–Early Cretaceous, we find that rifting in the East Shetland Basin was protracted from pre-Triassic to Cretaceous. We find that, during the Jurassic, most pre-Jurassic normal faults were buried and in some cases cross-cut by newly formed faults, with only a few being reactivated. Previously developed faults thus had only a limited control on the evolution and geometry of the later rift. We instead argue that strain migration and rift narrowing was linked to the evolving thermal state of the lithosphere, an interpretation supporting the predictions of lithosphere-scale numerical models. Our study indicates that additional regional studies of natural rifts are required to test and refine the predictions of physical and numerical models, more specifically, our study suggests models not explicitly recognising or including thermal or rheological effects might over emphasise the role of discrete pre-existing rift structures such as normal faults.

1. Introduction

Continental extension marks the first stage of ocean basin formation, being associated with normal faulting and the development of rift basins (e.g. Nagel and Buck, 2007). Because continental breakup is protracted (i.e. several tens of millions of years; e.g., Ziegler and Cloetingh, 2004), and the related extensional forces are complex, many rifts are products of not one, but multiple phases of extension (e.g., the northern North Sea, Færseth, 1996; the Gulf of Thailand, Morley et al., 2004; and the Galicia rifted margin, Reston, 2005). Unlike polyphase rifts, in which the rheologic character changes due to progressive deformation and thinning during a single extension phase (e.g., fault block rotation and locking, Reston, 2005; ductile to brittle deformation, Lavier and Manatschal, 2006), multiphase rifts have been exposed to multiple episodes of extension (with or without a change in extensional direction), with extension phases possibly separated by phases of quiescence.

The geometry and evolution of such multiphase rifts, especially during the latter stages of their development, may thus be controlled by reactivation of discrete, pre-existing, upper crustal

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structures, such as normal faults, or more pervasive fabrics developed during earlier rift or orogenic periods (e.g., Badley et al., 1988; Strecker et al., 1990; Coward, 1993; Færseth, 1996; Keep and McClay, 1997; Odinsen et al., 2000; Gawthorpe et al., 2003; Morley et al., 2004; Bellahsen and Daniel, 2005; Cowie et al., 2005; Reston, 2005; Henza et al., 2010, 2011; Nixon et al., 2014; Whipp et al., 2014; Duffy et al., 2015; Phillips et al., 2016). However, because sedimentary basins formed during the early stages of multiphase rifting are progressively buried and structurally overprinted during later stages of rifting, it can be difficult to assess the role pre-existing faults play in controlling subsequent rift geometry. In some cases, older faults are abandoned and may in fact be cross-cut by newly formed structures (e.g., Lee and Hwang, 1993; Thomas and Coward, 1995; Reston, 2005; Tomasso et al., 2008; Bell et al., 2014).

Scaled physical models provide useful insights into the geometry and kinematics of upper-crustal, fault networks during multiphase rifts, predicting pre-existing faults are likely to be at least partly reactivated if the stretching direction changes by $<45°$ between extension events (Henza et al., 2010). Although powerful, the majority of these models tend to focus on relatively small fault networks and do not incorporate the superimposed effects of lithosphere-scale heterogeneities (e.g. rheology and temperature). Unlike crustal-scale physical models, lithosphere-scale numerical models can explicitly capture variations in lithosphere properties at a scale appropriate to multiphase rifts associated with continental breakup. Lateral variations in lithosphere rheology and temperature, which may be imposed by and inherited from earlier phases of stretching, may also play a key role in controlling the location and style of rifting (e.g. Buck et al., 1999; Odinsen et al., 2000; Huismans et al., 2001; Behn et al., 2002; Ziegler and Cloetingh, 2004; Cowie et al., 2005; Huismans and Beaumont, 2007; Nagel and Buck, 2007; Naliboff and Buiter, 2015). For example, Naliboff and Buiter (2015) use finite element models to show that, if the period of tectonic quiescence between rift phases is sufficiently long, then the integrated strength of the first-phase rift axis site can recover, leading to large-scale rift migration and the abandonment of first-phase faults. However, most lithosphere-scale models are of insufficient spatial resolution (>1 km) to allow direct investigation of the impact of individual pre-existing faults on the geometry and evolution of subsequent fault networks and the rift basins they control.

Outcrop studies can reveal the geometry and kinematic development of large rift-related fault arrays (i.e., a kinematically linked group of faults that are 10's to 100 km of length) at a relatively high-level of spatial and temporal precision (e.g., Strecker et al., 1990; Gawthorpe et al., 2003; Morley et al., 2004). However, such studies are typically limited by the quantity and quality of outcrop, with structures and stratigraphy associated with only one rift stage being exposed. In contrast, subsurface studies utilising long (10's to 100 km), widely spaced (>5 km) 2D seismic profiles allow us to define the basin-scale geometry of structures associated with individual tectonic phases in multiphase rifts, but these lack the spatial detail needed to investigate how pre-existing faults behave on the scale of individual fault systems (i.e., kinematically linked group of faults that are 1-to several 10's of km long) (e.g., Badley et al., 1988; Coward, 1993; Thomas and Coward, 1995; Færseth, 1996; Reston, 2005). More insightful are subsurface studies using 3D seismic reflection data (e.g., Tomasso et al., 2008; Nixon et al., 2014; Whipp et al., 2014; Duffy et al., 2015). These studies are able to highlight the sometimes subtle influence of pre-existing faults on subsequent fault system development. However, these typically only consider a limited time-interval (<50 Myr) due to the limited depth of imaging, thus do not cover the full multiphase rift history. Furthermore, as individual 3D surveys typically cover only ∼500 km^2, these studies are usually too small to assess the relative influence of lithospheric-scale processes.

In this study we combine well log-tied 2D and multiple merged 3D seismic reflection surveys (∼10,000 km^2) from the East Shetland Basin, northern North Sea (Fig. 1), to resolve the structure of the basin from pre-Triassic to the present day. Using these observations we address the following questions: (i) do pre-existing normal faults control rift geometry?; and (ii) does the lithosphere thermal and rheological state and structure influence rift geometry?. By addressing these questions, we test the predictions of physical and numerical models of multiphase rifting. Moreover, unlike most previous studies (see above), our extensive, high-quality dataset allows us to document how pre-existing normal faults throughout a regional fault array accommodate later extension.

2. Geological setting

The East Shetland Basin is located in the northern North Sea, on the western flank of the North Viking Graben (Fig. 1a). The present day geometry of the East Shetland Basin is dominated by structures related to the last major phase of rifting during the Middle-to-Late Jurassic. These structures comprise N- to NE-trending, east-dipping normal faults (Cormorant, Pelican, Heather, Murchison, Osprey, Hutton, Ninian, Statfjord, Brent, Strathspey, Alwyn, and Tordis faults) bounding 60–75 km long, 15–25 km wide half-grabens in the middle and eastern part of the East Shetland Basin (Fig. 1c). The East Shetland Platform lies along the western margin of the East Shetland Basin, forming a high that is bounded by two major east-dipping faults (Hudson and West Margin faults), whereas the Tern-Eider Ridge represents a prominent horst block located in the NW of the East Shetland Basin that is flanked by the Tern and Eider faults (Fig. 1c). The Magnus and Tern sub-basins lie to the north and south of the Tern-Eider Ridge, respectively, and the Ninian sub-basin is located in the southern part of the East Shetland Basin (Fig. 1c).

Major phases of basement-involved extension occurred in the Late Palaeozoic to Mesozoic (e.g., Coward, 1990, 1993; Platt, 1995), with most authors agreeing that the northern North Sea experienced two discrete phases of extension in the Permian–Triassic and Middle-to-Late Jurassic (e.g., Badley et al., 1988; Lee and Hwang, 1993; Thomas and Coward, 1995; Færseth, 1996; Odinsen et al., 2000). The northern North Sea region is a moderately stretched rift, with low β-values (i.e. stretching-values). Both extension phases were of approximately the same magnitude, reaching β-values of ∼1.4 across the entire width of the northern North Sea, and 1.3 and 1.1 across the East Shetland Basin for the Permian–Triassic and Middle-to-Late Jurassic, respectively (Roberts et al., 1995; Færseth, 1996; Odinsen et al., 2000).

Many authors suggest Late Palaeozoic to Mesozoic rift development was influenced, if not directly controlled, by the inherited Caledonian and Devonian structural framework, both in the East Shetland Basin (Coward, 1990, 1993; Rattey and Hayward, 1993; Platt, 1995; Thomas and Coward, 1995) and elsewhere (e.g., Doré et al., 1997), although this view has recently been challenged (e.g., Reeve et al., 2013). Reactivation of large Permian–Triassic faults during Middle-to-Late Jurassic rifting throughout the northern North Sea has been proposed (e.g., Badley et al., 1988; Færseth, 1996; Odinsen et al., 2000; Cowie et al., 2005). However, in the East Shetland Basin, an alternative interpretation, envisaging that Permian–Triassic faults are partly cross-cut and only partly reactivated during Middle-to-Late Jurassic rifting, is suggested (e.g., Lee and Hwang, 1993; Thomas and Coward, 1995; Tomasso et al., 2008). For example, Tomasso et al. (2008) propose that west-dipping Triassic normal faults developed in the SE of the East Shetland Basin and were subsequently cross-cut by

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