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Fault growth and interactions in a multiphase rift fault network: Horda Platform, Norwegian North Sea

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ABSTRACT

Physical models predict that multiphase rifts that experience a change in extension direction between stretching phases will typically develop non-colinear normal fault sets. Furthermore, multiphase rifts will display a greater frequency and range of styles of fault interactions than single-phase rifts. Although these physical models have yielded useful information on the evolution of fault networks in map view, the true 3D geometry of the faults and associated interactions are poorly understood. Here, we use an integrated 3D seismic reflection and borehole dataset to examine a range of fault interactions that occur in a natural multiphase fault network in the northern Horda Platform, northern North Sea. In particular we aim to: i) determine the range of styles of fault interaction that occur between non-colinear faults; ii) examine the typical geometries and throw patterns associated with each of these different styles; and iii) highlight the differences between single-phase and multiphase rift fault networks. Our study focuses on a *ca.* 350 km^2 region around the >60 km long, N–S-striking Tusse Fault, a normal fault system that was active in the Permian–Triassic and again in the Late Jurassic-to-Early Cretaceous. The Tusse Fault is one of a series of large (>1500 m throw) N–S-striking faults forming part of the northern Horda Platform fault network, which includes numerous smaller (2–10 km long), lower throw (<100 m), predominantly NW–SE-striking faults that were only active during the Late Jurassic to Early Cretaceous. We examine how the 2nd-stage NW–SE-striking faults grew, interacted and linked with the N–S-striking Tusse Fault, documenting a range of interaction styles including mechanical and kinematic isolation, abutment, retardation and reactivated relays. Our results demonstrate that: i) isolated, and abutting interactions are the most common fault interaction styles in the northern Horda Platform; ii) pre-existing faults can act as sites of nucleation for 2nd-stage faults or may form mechanical barriers to propagation; iii) the throw distribution on reactivated 1st-stage faults will be modified in a predictable manner if they are intersected or influenced by 2nd-stage faults; iv) sites of fault linkage and relay-breaching associated with the first phase of extension can act as preferential nucleation sites for 2nd-stage faults; and v) the development of fault intersections is a dynamic process, involving the gradual transition from one style to another.

1. Introduction

Faults that develop during a single phase of extension typically strike sub-perpendicular to the extension direction and show an en échelon or colinear configuration (e.g. Gawthorpe and Leeder, 2000) (Fig. 1). Faults with strikes that are oblique to the main rift trend (herein termed ‘non-colinear faults’) can also develop during a single rift phase, commonly due to breaching of relay zones (e.g. Trudgill, 2002), flexure and gravity-driven sliding of the cover above weak layers (e.g. overpressured mudstone or and salt; e.g. Stewart and Clark, 1999) and the development of ‘release’ faults (e.g. Destro, 1995). Furthermore, non-colinear faults also develop in response to: i) perturbations in the local stress field around pre-

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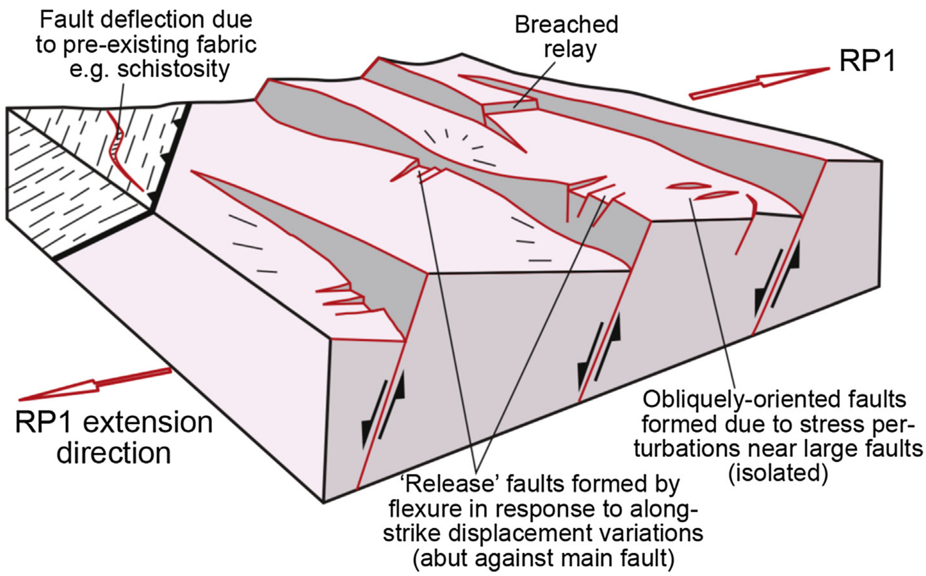

Fig. 1. Block model showing simple large-scale co-linear faults developed during a single-phase of rifting as well as the typical locations of any non-colinear faults that may develop (RP1 = rift phase 1, arrows indicate extension direction).

existing or broadly synchronous normal faults (Maerten et al., 1999, 2002); ii) compaction and dewatering, which in some cases leads to radially-isotropic strain expressed as 'polygonal' faulting (e.g. Cartwright and Lonergan, 1996; Cartwright and Dewhirst, 1998); and iii) the anisotropic effects of pre-existing fabrics that are oriented obliquely to the extension direction (e.g. Morley et al., 2004) (Fig. 1; see also Reeve et al., 2015 for a synthesis). However, the development of non-colinear faults in many of these cases is not pervasive across the fault network and the range of styles of interaction and overall influence of fault interactions in the evolution of the fault network is relatively low (Fig. 1).

In contrast, in multiphase rifts, and particularly where the extension direction during each rift phase differs, faults formed in the first rift phase influence how strain is accommodated in the upper crust in the second rift phase (e.g. Keep and McClay, 1997; Bellahsen and Daniel, 2005; Henza et al., 2011; Whipp et al., 2014). In this situation the later rift phase is characterised by reactivation of pre-existing faults from the 1st-rift stage and/or nucleation of newly formed, 2nd-stage faults in previously unruptured crust, which generally strike sub-perpendicular to the new extension direction (e.g. Bailey et al., 2005; Henza et al., 2010, 2011; Whipp et al., 2014). Fault networks in multiphase rifts are therefore prone to comprise of pervasive non-colinear fault sets, with interaction and intersections between the non-colinear faults common, as is observed in the Jeanne D'Arc rift (e.g. Sinclair and Withjack, 2008), Gulf of Aden (Bellahsen et al., 2006), Gulf of Thailand (e.g. Morley et al., 2004; Morley, 2007), Alaska (Nixon et al., 2014) and the North Sea (Badley et al., 1988; Færseth, 1996; Odinsen et al., 2000; Whipp et al., 2014).

Much of our understanding of how non-colinear faults and fault interactions evolve in multiphase rifts is based on predictions from physical models (e.g. McClay and White, 1995; Bellahsen and Daniel, 2005; Henza et al., 2010, 2011; Chattopadhyay and Chakra, 2013). While these physical models provide important information on the plan-view evolution of faults and fault interactions, the true 3D geometry of the faults and interaction styles remain unknown. Furthermore, there is a general lack of observations of different fault interaction styles from outcrop or subsurface natural examples, although Nelson (2006) and Nixon et al. (2014) provide notable exceptions.

In this study we examine a fault network in a natural multiphase rift to: i) identify a range of styles of fault interaction and/or linkage between 1st and 2nd-stage faults; ii) examine the tipline geometries, branchline characteristics and throw patterns associated with each interaction style; and iii) develop an understanding of how fault interaction styles evolve. To achieve this we integrate observations from a 3D seismic reflection and borehole dataset that covers the northern Horda Platform array, Horda Platform, northern North Sea. This setting is ideal for this study because previous studies demonstrate the area was subject to two rift events, which resulted in the formation of fault sets with different dominant strikes (Badley et al., 1988; Færseth, 1996; Odinsen et al., 2000; Whipp et al., 2014). Furthermore, the relatively shallow burial of the area means faults and branchlines are well-imaged, and an abundance of borehole data allows us to constrain the age of growth strata adjacent to the faults, and hence constrain the temporal evolution of the fault array. Using this information, we improve our understanding of how pre-existing faults influence the development of subsequent fault networks and present a template of fault interaction styles that will aid structural mapping in seismic datasets lacking such clear imaging of faults and their geometric relationships.

2. Geological framework

2.1. Regional tectonic evolution

The crystalline basement of the northern North Sea was influenced by contractional episodes in the Caledonian (460–400 Ma) and Variscan (400–300 Ma) orogenies (e.g. Ziegler, 1975). During the Devonian, post-orogenic crustal relaxation resulted in the development of major extensional shear zones and intermontane basins, such as those preserved onshore western Norway (e.g. Fossen, 1992; Vetti and Fossen, 2012). These extensional shear zones formed a crustal fabric which is interpreted to have influenced the development of the North Sea basin by modifying the geometry of Mesozoic rift systems and influencing the distribution of thermally-driven Cenozoic subsidence (e.g. Glennie, 1987; Ziegler, 1990; Stewart et al., 1992; Bartholomew et al., 1993; Smethurst, 2000).