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The topology of evolving rift fault networks: Single-phase vs multi-phase rifts

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ABSTRACT

Rift fault networks can be complex, particularly those developed by multiple periods of non-coaxial extension, comprising non-colinear faults with many interactions. Thus, topology, rather than simple geometry, is required to characterise such networks, as it provides a way to describe the arrangement of individual faults in the network. Topology is analysed here in terms of nodes (isolated I nodes or connected Y or X nodes) and branches (I–I, I–C, C–C branches). In map view, the relative proportions of these parameters vary in natural single- and multi-phase rift fault networks and in scaled physical models at different stages of development and strain. Interactions in single-phase rifting are limited to fault splays and along-strike fault linkage (I node and I-I or I–C branch dominated networks), whereas in multi-phase rifting the topology evolves towards Y node and C–C branch dominated networks, with the degree of connectivity increasing with greater strain. The changes in topology and network connectivity have significant implications for fluid flow and reservoir compartmentalisation studies. Furthermore, topology helps to distinguish single and multiple phase extension (i.e. tectonic histories), and thus provide constraints on the geodynamic context of sedimentary basins.

1. Introduction

Faults in rift systems form complex networks that can have a variety of configurations. Fault networks formed during a single extension event are dominated by sub-parallel and overlapping faults, whereas networks formed through multiple extension phases show a range of fault orientations and interactions (cf. Gawthorpe and Leeder, 2000; Fossen et al., 2005; Henza et al., 2011; Whipp et al., 2014; Nixon et al., 2014a; Duffy et al., 2015). Most studies of rift fault networks and their evolution are based on geometrical and kinematic parameters of individual faults, such as fault length, orientation, density, displacement and strain (e.g. Meyer et al., 2002; Walsh et al., 2003; Nixon et al., 2014b; Peacock et al., 2016). However, these analyses largely neglect the arrangement and relationships between faults – the network topology. Those studies that do examine the nature of interactions between faults, particularly in multiphase networks, focus on determining the displacement patterns and orientations of faults (e.g. Nelson, 2006; Henza et al., 2011; Nixon et al., 2014a; Duffy et al., 2015) that help for interpreting such interactions. However, need exists for a more consistently applied and quantitative analysis that allows fault networks to be easily compared.

Fault networks and fault interactions can be described by their geometry, topology, kinematics, dynamics and mechanics (Peacock et al., 2016). Here, we focus on fault network topology, which describes and quantifies the different spatial relationships between faults, with particular focus on fault terminations and different fault intersections. Unlike geometrical parameters that are measured by defined dimensional units, topological parameters are dimensionless, and thus scale invariant and unchanged by any transformations (Jing and Stephansson, 1997; Sanderson and Nixon, 2015). Topology is important as it provides an efficient method for characterizing fault networks and also quantifies the network connectivity such that fault networks can be easily

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compared (Morley and Nixon, 2016). Interconnected fault networks can act either as conduits or barriers to fluid flow (Leveille et al., 1997; Aydin, 2000), therefore, determining the topology of fault networks has implications for fluid flow (e.g. Adler and Thovert, 1999; Manzocchi, 2002), as well as the structural configuration and compartmentalization of hydrocarbon reservoirs and aquifers (e.g. Richards et al., 2015).

Fault networks evolve in response to increasing finite strain. As constituent faults grow, interact and link, both their geometry (e.g. Cartwright et al., 1995; Cowie, 1998; Gawthorpe and Leeder, 2000; Ackermann et al., 2001; Walsh et al., 2003) and topology will change. The arrangement or pattern of faults within rifts is related to influences on the growth and development of the networks, including, strain magnitude, multiple phases of extension, interaction and reactivation of pre-existing structures, and local stress variations (e.g. Reeve et al., 2015). As a result, fault networks in different rift systems show a wide range of topologies (Morley and Nixon, 2016).

Here, we investigate topological variability, using map views of fault networks from both natural examples and scaled physical models, focusing on the effects of increasing strain and multiple phases of extension. We illustrate how the topology of both single- and multi-phase fault networks evolves in response to increasing strain, yielding important insights into how the configuration, maturity and connectivity of fault networks change during progressive deformation. To examine the range of topologies in rift fault networks, we examine natural examples from a variety of rift settings. To focus more explicitly on the effects of increasing strain and multi-phase rifting on fault networks, we analyse a series of scaled wet-clay physical models (from Henza et al., 2011) that have a known strain history. This modelling approach allows us to examine: i) topological differences between single- and multi-phase normal fault networks; ii) topological evolution in response to increasing strain; and iii) the influences of a second phase of non-coaxial extension on the topology of an evolving network. We compare the topology of natural examples of single- and multi-phase rifts with the physical models to validate the use of topology as a characterisation tool for rift fault networks.

2. Methodology

2.1. Node and branch topology

The topology of a fault network in plan view is considered in terms of nodes and branches between nodes (Fig. 1). Nodes are classified into three types: I nodes for isolated fault tips; Y nodes for abutting or splaying intersections; and X nodes representing crossing intersections (Fig. 1). As branches have two nodes at their ends they can also be classified into three types: isolated I–I branches with no connecting nodes; singly connected I–C branches with one connecting node; or doubly connected C–C branches with two connecting nodes (Fig. 1), where C would be either an X or Y node. The proportions of the different node and branch types define the network topology and these values can be plotted on node and branch triangles, allowing networks to be compared (Fig. 1b) (Manzocchi, 2002; Sanderson and Nixon, 2015).

Topology can be used to quantify and compare the degree of connectivity within and between networks using topological parameters derived from the number counts of the different node types (N_I, N_Y, N_X). One such parameter is the average number of connections per branch (C_B):

$$C_B = (3N_Y + 4N_X)/N_B$$

Where the N_B is the number of branches given by

$$N_B = (N_I + 3N_Y + 4N_X)/2$$

As branches can be isolated, singly connected or doubly connected, C_B ranges from 0 to 2 and can be directly contoured onto the node and branch triangles (Fig. 1) (for full derivation see Sanderson and Nixon, 2015).

2.2. Application to natural networks and physical models

We apply node and branch topology to five natural fault networks, based on published maps of fault polygons and predominantly interpreted from horizons imaged in 3D seismic reflection data (Fig. 2). The fault maps demonstrate that a wide range of fault configurations can develop in single- and multi-phase rifts with differing maturities, including: sub-parallel and overlapping faults (Fig. 2a); zig-zag fault trends with abundant splays (Fig. 2b and c); and orthogonal fault trends that abut and cross-cut one another (Fig. 2d and e).

To investigate and better understand the variations in topology between different natural fault networks, we analysed fault traces from the published wet clay, physical models of Henza et al. (2011) (Fig. 3). In these models, the strain increments throughout a single extension phase (E1) and a second phase of non-coaxial extension (E2) are known, with E2 oriented at 45° to E1 (see Henza et al., 2011; for model parameters and outputs). The fault geometry and network topology of the physical models are captured at different time steps during development of the fault network, and the boundary strain conditions for each fault map are tightly constrained. Therefore, the models allow us to accurately examine the effects of increasing strain and multiple phases of extension on network topology and connectivity. We focus on three different cases (Fig. 3): i) increasing strain in a single extension phase; ii) addition of a second extension phase after a relatively low strain first phase; and iii) addition of a second extension phase after a relatively high strain first phase. The results from the analysis of the models can be used to inform the interpretation of strain histories derived from mapped seismic horizons in natural rifts, where the strain history can often only be inferred by displacement backstripping of the final fault network.

3. Geometry and topology of natural rift fault networks

We describe the map-view fault configuration and topologies of each natural fault network in Fig. 2 to determine how the different network configurations are expressed topologically and to quantify the differences in connectivity (node and branch data is shown in Table 1). We begin with simple single-phase networks dominated by isolated faults, before concluding with more complex multi-phase networks characterised by pervasive orthogonal fault sets.

3.1. Cartier Trough, Timor Sea, offshore NW Australia

The southeast corner of the Cartier Trough, Timor Sea, offshore NW Australia provides a type example of a highly-immature single-phase rift fault network (Fig. 2a). The network comprises a series of Plio-Pleistocene, WSW-ENE-striking faults that dip to the NNW and SSE (Pattillo and Nicholls, 1990; Woods, 1992; Nicol et al., 1995). Viewed on a pre-rift, lower Miocene horizon, the fault traces are sub-parallel, overlapping and irregularly-spaced, with the map dominated by short (<5 km-long) fault segments (Fig. 2a). This example reflects the simplest type of network where, with the exception of a few splays, almost all of the faults are isolated and across-strike connectivity is negligible. As such, the network topology is dominated by I nodes (96%) and I-I branches (81%) (Fig. 4). Only the presence of a few fault splays, features expressed