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Topological characteristics of simple and complex normal fault networks

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ABSTRACT

2-D, map-view topological analysis of ten natural and two analogue fault networks was undertaken. The fault arrays range from simple, low-displacement systems, to complex systems arising from multiple stages of deformation, or exhibiting complex local rotation of stresses. Classification of fault arrays was based on fault terminations (I-nodes), splaying and abutting geometries (Y-nodes) and cross-cutting relationships (X-nodes), which permit relatively quick and simple ways of analysing fault terminations and connectivity. Many of the fault networks are predominantly composed of I- and Y-nodes with at most only a minor X-node population, hence discrimination of significant differences between fault networks using just this type of analysis is limited. Subdividing Y-nodes into splaying (Ys), abutting (Ya) and cross-cutting (Yc) types, displaying the data on Ys-Ya-Yc node triangles, as well as generating equivalent networks defined by vertices and edges provides additional information for defining fault networks. Comparison of the Ys-Ya-Yc node triangle and the excess kurtosis of vertice degree distribution identifies seven distinct types of network that show meaningful differences. Such quantitative descriptions are useful for comparing the results of analogue and numerical models with natural examples as well as assessing fault network connectivity, which has implications for the structural interpretation of reservoirs and aquifers. A wide variety of factors contribute to variations in fault networks such as variations in strain, stress rotation with time, fabric inheritance, and stress deflection. While topology cannot be used to identify specific mechanisms, some topological characteristics can help narrow the likely mechanism particularly when used in conjunction with more traditional techniques and observations.

1. Introduction

There have been considerable advances, particularly recently, in understanding the complexity of normal fault development in rifts as a result of pre-existing fabrics, multiple phases of rifting, and rotation of extension direction with time from both natural examples and modelling (e.g. McClay and White, 1995; Keep and McClay, 1997; Morley, 1999a,b, 2010, in press; Morley et al., 2004; Corti et al., 2007, 2012; Henza et al., 2010, 2011; Nixon et al., 2014; Tong et al., 2014; Whipp et al., 2014; Bladon et al., 2015; Duffy et al., 2015; Henstra et al., 2015; Reeve et al., 2015). In these studies fault populations have typically been described in terms of fault azimuths, fault displacement characteristics, fault patterns and evolving slip sense with time. These characteristics are generally sufficient for identifying the causes of fault patterns that depart from typical, simple orthogonal rifting patterns. However, characterization of how the faults terminate, join, splay and intersect permits further quantitative description of the fault networks, and leads to a deeper understanding of variations within and between normal fault networks. Sanderson and Nixon (2015) discuss a simple topology-based methodology that can be used to characterize fracture networks based on node types (fracture terminations, joins, splays and intersections). This methodology has practical benefits for populating incomplete data sets with fracture arrays when trying to model fluid flow in rocks (also see Manzocchi, 2002; Andresen et al., 2013).

Geometry and topology in mathematics are closely related but differ in that geometry is concerned with the size, shape, and spatial properties of objects, which are defined by measurable unit dimensions. Topology is dimensionless instead describing the

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arrangement of and geometrical relationships between spatial objects, and is invariant to scale, strain and continuous map-type transformations (e.g. Janich, 1984; Jing and Stephansson, 1997; Sanderson and Nixon, 2015). In network topology the inherent degree of connectivity between objects is used to describe characteristics of physical (e.g. railway networks) or logical (e.g. signals, data) layouts of connected branches and nodes that communicate in some way (e.g. Barabási and Stanley, 1995; Albert and Barabási, 2002).

The topology of geological fracture networks can be defined by nodes at fracture intersections and terminations, and vertices at fracture centre points (Figs. 1 and 2). Although fracture networks are 3-dimensional features, fracture topology can be addressed as 2-dimensional networks, in particular from maps and rock pavement outcrops (Manzocchi, 2002; Valentini et al., 2007a,b; Sanderson and Nixon, 2015). This two dimensional approach works well for normal faults where the majority of fault splays and intersections can be captured on seismic data by horizontal time slices from horizon maps, but is more problematic for complex 3-D arrays of fractures and joints. However, it should be noted that normal fault splays with sub-horizontal branch lines and conjugate normal faults with sub-horizontal cutoff lines will not be captured by analysis of map-view faults.

There is considerable utility in describing fault networks

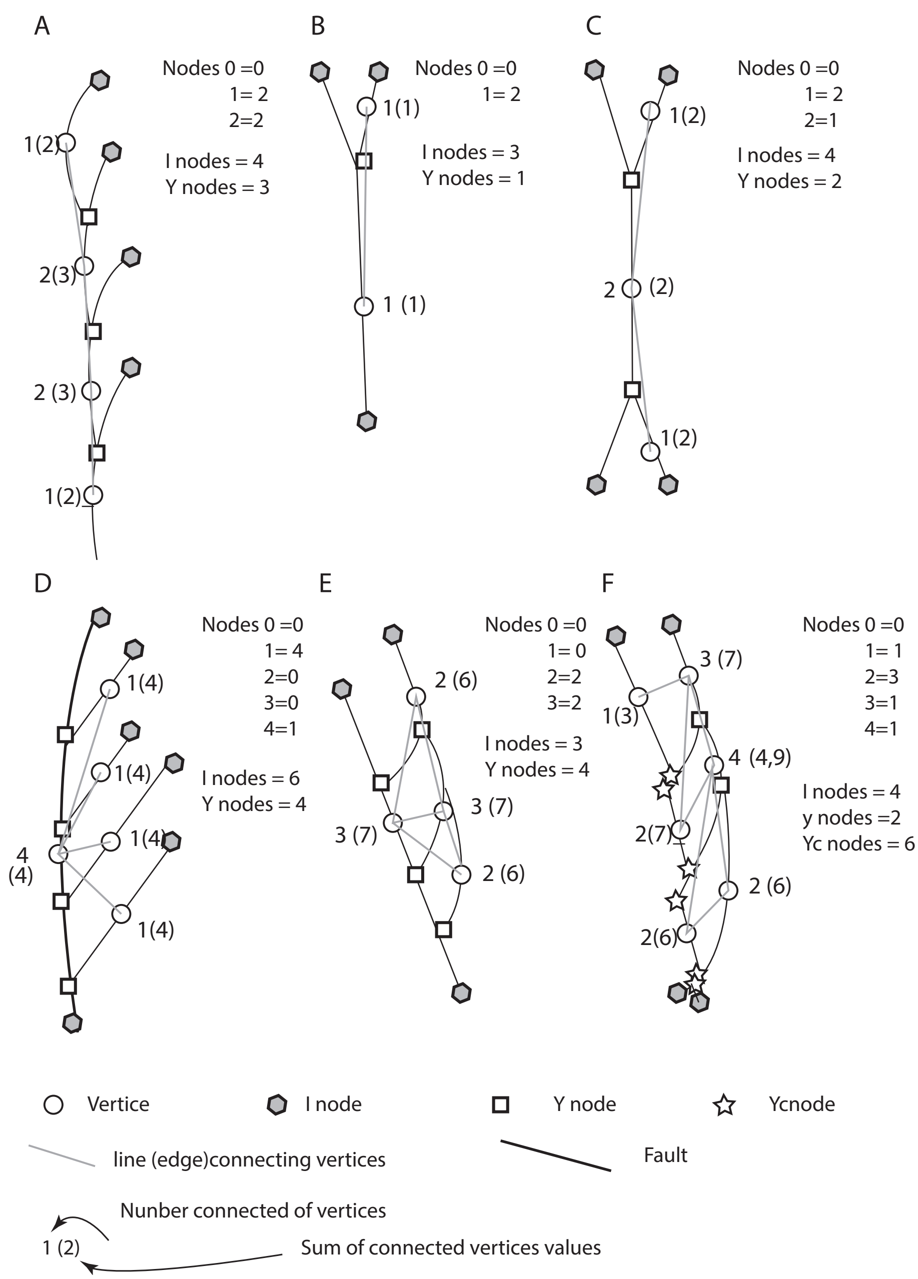

Fig. 1. Schematic illustration of some basic normal fault patterns, and how the nodes and vertices associated with the different fault patterns change. A) Linked, curved faults, possibly due to linkage along older fault trend along N–S trend. B) Splaying fault. C) Doubly splaying fault. D) Long fault on N–S trend with abutting NE–SW oblique trending faults. E) Single segment fault, with abutting fault that curve from multi-segmented fault (similar to A). F) Similar fault set up to E) but instead of the curved faults exhibiting an abutting relationship, they exhibit a cross-cutting relationship. Note that because an offset of one fault is caused by the cross-cutting fault there are two Yc nodes produced for each cross-cutting fault.