Journal of Structural Geology 39 (2012) 253–267

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Segmentation and growth of an obliquely reactivated normal fault

M. Giba [a,*], J.J. Walsh [a], A. Nicol [b]

[a] Fault Analysis Group, UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland
[b] GNS Science, PO Box 30368, Lower Hutt, New Zealand

ARTICLE INFO

Article history:
Received 21 November 2010
Received in revised form
23 December 2011
Accepted 18 January 2012
Available online 30 January 2012

Keywords:
Normal fault segmentation
Oblique reactivation
Relay zone
Displacement transfer
Coherent fault model

ABSTRACT

Detailed kinematic analysis of a large (1800 m maximum displacement) reactivated normal fault in the Taranaki Basin, New Zealand, has been conducted using high quality 3D seismic data. The Parihaka Fault is approximately north-south striking in basement, where it accrued Late Cretaceous to Early Eocene displacements in response to east-west extension, and was obliquely reactivated by NW–SE extension in the Pliocene. Reactivation resulted in upward propagation, newly formed segmentation and up-dip clockwise rotation of the fault surface by up to $\sim 20^{\circ}$ from the strike of the basement fault. Fault segmentation, and map-view soft-linkage by relay zones in post Miocene strata, was synchronous with the formation of antithetic faults in Late Miocene strata at bends in the fault surface. Fault segment lengths, antithetic faults and relay zone dimensions were formed geologically instantaneously during initial reactivation of the main fault at 3.7–3.4 Ma (i.e. within the first $\sim 10\%$ of faulting). Rapid formation of Pliocene fault segments is followed by displacement accumulation without an increase in fault segment length until eventual relay breaching when continued ramp rotation is unsustainable. This evolutionary history is consistent with a model in which arrays of fault segments are, from inception, components of a single coherent structure.

1. Introduction

Faults in multi-layered sequences typically comprise segments separated by relay zones across which displacement is transferred (Fig. 1a). Formation of segmented normal faults in map-view can be explained by two end-member models, the "isolated fault model" (e.g., Walsh and Watterson, 1988; Cowie and Scholz, 1992; Gillespie et al., 1992; Dawers and Anders, 1995; Huggins et al., 1995; Trudgill and Cartwright, 1994; Cartwright et al., 1995; Schlische et al., 1996; McLeod et al., 2000) and the "coherent fault model" (Childs et al., 1995; Walsh et al., 2002, 2003). The isolated fault model requires that an array of fault segments grows by tip line propagation and the eventual, and incidental, lateral overlap and interaction of initially isolated faults (Fig. 1b), while in the coherent model the array is established rapidly by individual segments which are kinematically related components of essentially the same structure, perhaps even linking into a single continuous fault surface at depth (Fig. 1c; Walsh et al., 2003). Distinction between these models is best illustrated where kinematic constraints can be derived from syn-sedimentary faults providing a basis for defining fault propagation and displacement accumulation through time. In many circumstances where only the map-view patterns of a fault array are observable, a distinction between these models cannot easily be made and it is tempting to assume that fault propagation is entirely within the plane of inspection, an assumption which inevitably favours the isolated fault model (e.g., Cartwright et al., 1995; McLeod et al., 2000). In this paper we describe an array of fault segments which on both geometric and kinematic grounds can be shown to subscribe to the coherent model, both in 2D (i.e. map-view) and 3D. Using constraints from high quality 3D seismic reflection lines, we highlight the close geometric and kinematic relations between segments that from inception are part of the same structure, a scenario that is consistent with the relatively small number of studies where the propagation and growth of fault segments has been documented (e.g., Childs et al., 1995, 2003; Meyer et al., 2002; Walsh et al., 2003).

While the kinematic interdependence of fault segments is a requirement of the coherent model, a variety of related issues have yet to be fully resolved, such as how rapidly relay geometries establish and the extent to which the relay-bounding fault segments continue to propagate as the relay evolves. In this paper these questions are examined using 3D seismic reflection data to

* Corresponding author. Present address: TOTAL E&P UK Limited, Geoscience Research Centre, Crawpeel Road, Altens, Aberdeen AB12 3FG, UK. Fax: +44 (0) 1224 233026.
E-mail address: marc.giba@total.com (M. Giba).

0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2012.01.004

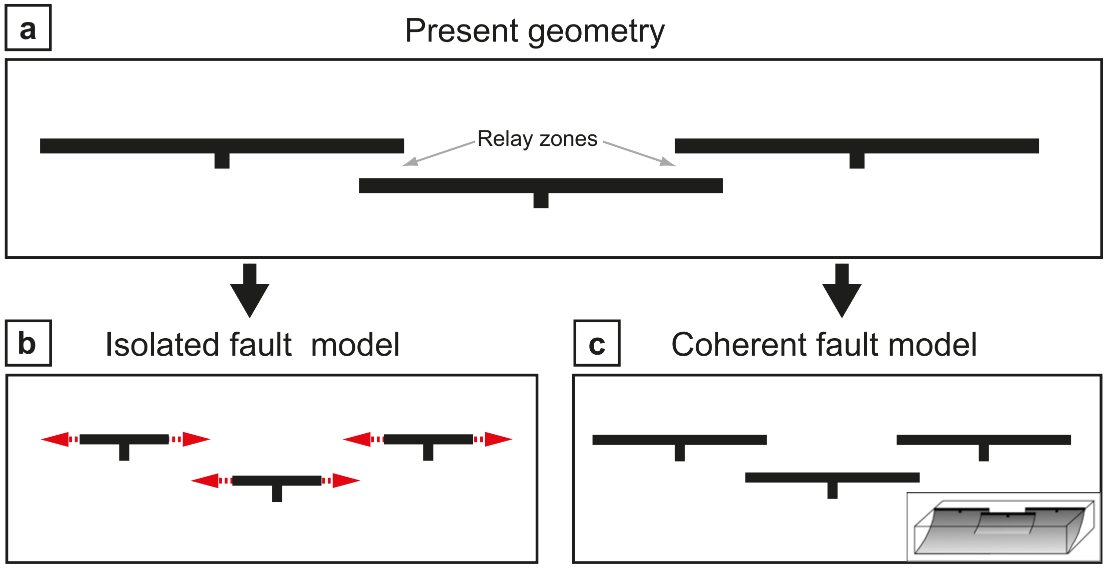

Fig. 1. a) Schematic map-view geometry of a segmented normal fault comprising segments soft-linked by relay zones. Fault segmentation can be explained by two opposing segmentation models – the "isolated fault model" (b) and the "coherent fault model" (c). b) The isolated fault model requires that the segmented map-view pattern establishes by the progressive lateral propagation (indicated by arrows), incidental interaction and overlap of faults which were originally geometrically and kinematically isolated from each other. Initial fault lengths are significantly shorter than final fault lengths. c) In the coherent fault model segments are part of a larger geometrically and kinematically coherent structure. Fault segment lengths are believed to establish geologically instantaneously and may splay from a common fault surface at depth (see inset) (after Walsh et al., 2003).

analyse the growth history of the highly segmented Parihaka Fault. Our study shows that oblique reactivation of the Parihaka Fault in the Early Pliocene led to rapid formation of an array of en-échelon fault segments which are hard-linked with a continuous pre-existing fault surface at depth and soft-linked by relay zones in map-view at shallow depths. Kinematic analysis and displacement backstripping of the fault within syn-faulting Plio-Pleistocene strata shows that two overlapping fault segments developed geologically instantaneously in the Early Pliocene, with rapid initial formation of fault segment lengths and relay zone dimensions in map-view. Following the establishment of segment lengths fault growth was dominated by displacement accumulation and progressive rotations of relatively stable relay ramps until eventual breaching. This fault evolution is consistent with the coherent fault model of Walsh et al. (2003).

2. Geological background and data

The Parihaka Fault is located along the western margin of the Taranaki Basin which is mainly west of the North Island of New Zealand (Fig. 2a). The Taranaki Basin has had a multiphase deformation history, with extension during the Late Cretaceous to Early Eocene (ca 84–50 Ma), followed by contraction from the Late Eocene to Recent (ca 40–0 Ma) and by Late Miocene to Recent backarc extension (12–0 Ma). The temporal overlap in shortening and extension during Late Miocene to Recent is explained by spatial variations within the Taranaki Basin, with shortening occurring in the south and extension in the north (Giba et al., 2010). Late Cretaceous to Early Eocene rifting (Fig. 2b) (King and Thrasher, 1996; Giba, 2010) was associated with breakup of Gondwana. Late Eocene and younger tectonic evolution of the basin was driven by subduction of the Pacific Plate along the Hikurangi trough (Ballance, 1976; Walcott, 1987; Stern and Davey, 1989; King and Thrasher, 1992, 1996; Holt and Stern, 1994; Nicol et al., 2005; Stagpoole and Nicol, 2008). Backarc rifting during subduction resulted in reactivation of large north-south striking normal faults (with displacements of up to 3 km) during the Early Pliocene (~3.7 Ma). This latest phase of normal faulting produced extension in a NW–SE direction (Fig. 2c and d), at about 45° to the earlier east-west Cretaceous extension (King and Thrasher, 1996; Giba et al., 2010). The growth history of syn-rift normal faults active during the past 84 Myr is well-preserved by an almost complete sedimentary record, with up to 8 km of sedimentary rocks in the basin (Nodder, 1993, 1994; King and Thrasher, 1996; Nicol et al., 2005). Growth strata across the Parihaka Fault indicate that it accrued displacement during Late Cretaceous-Early Eocene extension and was reactivated with upward propagation of normal fault segments in the Early Pliocene (ca 3.7 Ma) (Fig. 3b).

Our 3D kinematic analysis of this fault is based on a high quality 3D seismic survey (Parihaka 3D) located offshore north of the Taranaki peninsula and covering an area of 1520 km^2 (Fig. 2). In- and cross-line spacings are 12.5 m and most structures are interpretable to 5.5 s two-way travel time (TWTT) (i.e. ca 8 km depth). Closely spaced seismic cross-sections and horizontal timeslices together with seismic attribute analyses (e.g., seismic variance timeslices ranging in depth from 0.25 s to 3 s TWTT; Fig. 4), were used to document details of the geometry of the Parihaka Fault. Stratigraphic, paleontological and geophysical information from four exploration wells (Arawa-1, Taimana-1, Witiora-1 and Okoki-1 – for well locations see Fig. 2d; International Department Dallas, 1984; NZ Oil and Gas, 1984; Crowley and Crocker, 1989; Arco Petroleum, 1992; Morgans, 2006), which are located within the survey area, were used to date and correlate seismic reflection horizons. Interpreted horizons in the 3D survey are part of, and tie to, a regional seismic interpretation of the entire Taranaki Basin (see Giba (2010) for details and extent of regional seismic interpretation). In total, 13 horizons ranging in age from 0.7 to 84 Ma were interpreted in the Parihaka 3D seismic reflection survey. Seven horizons younger then 4 Ma have been interpreted in order to describe in detail the Pliocene-Recent displacement history of the Parihaka Fault. Uncertainties in the ages of interpreted horizons are estimated to be about 10% (Nicol et al., 2005; Giba et al., 2010).

In the Taranaki Basin, high sedimentation rates have led to excellent preservation of displacements within the Late Cenozoic