Journal of Structural Geology 62 (2014) 52–64

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Fluid flow in fault zones from an active rift

H. Seebeck[a,b,*], A. Nicol[a], J.J. Walsh[c], C. Childs[c], R.D. Beetham[a,1], J. Pettinga[b]

[a] GNS Science, PO Box 30368, Lower Hutt 5010, New Zealand
[b] Dept. of Geol. Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[c] Fault Analysis Group, School of Geol. Sciences, University College Dublin, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 13 August 2013
Accepted 12 January 2014
Available online 22 January 2014

Keywords:
Fault zone
Fluid flow
Permeability
Connectivity

ABSTRACT

The geometry and hydraulic properties of fault zones are investigated for Mesozoic greywacke basement and Miocene sandstone from ~37 km of tunnels in the southern Taupo Rift, New Zealand. Localised groundwater inflows occur almost exclusively (≥~90%) within, and immediately adjacent to, fault zones. Fault zones in the contrasting lithologies comprise fault rock, small-scale faults, and fractures with thicknesses of 0.01–~110 m approximating power law distributions and bulk permeabilities of 10^{-9}–10^{-12} m^2. Variability in fault zone structure results in a highly heterogeneous distribution of flow rates and locations. Within basement ~80% of the flow rate occurs from fault zones ≥10 m wide, with ~30% of the total localised flow rate originating from a single fault zone (i.e. consistent with the golden fracture concept). No simple relationships are found between flow rates and either fault strike or hydraulic head, with ≤50% of fault zones in any given orientation flowing. A general positive relationship does however exist between fault zone thickness and maximum flow rate. Higher flow rates from larger fault zones may arise because these structures have greater dimensions and are more likely (than smaller faults) to be connected to other faults in the system and the ground surface.

1. Introduction

The hydraulic behaviour of fault zones is difficult to predict due to their spatially variable structure and permeability. Bulk flow rates through or along a fault zone are important for many practical applications, including geothermal and hydrocarbon production, and are dependent on a number of factors including permeability variations, structural anisotropy, pressure differentials and fluid viscosity (Caine et al., 1996; Evans et al., 1997; Cox, 1999; Wibberley et al., 2008; Manzocchi et al., 2010). Assessing the bulk flow properties of fault zones has been hindered by a general lack of *in situ* flow data which can be related to the structure of fault zones and surrounding rock-volume (Evans et al., 1997; Wibberley et al., 2008; Faulkner et al., 2010). Here we combine mapping of water flow rates and fault zone structure to examine the controls on flow in an area of normal faulting.

The impact of fault zones on flow depends primarily on their hydraulic properties relative to those of the surrounding wall rock. Where faults have permeabilities that are low relative to the wall rock they act as barriers to flow, and can for example compartmentalise hydrocarbon reservoirs (e.g., Manzocchi et al., 2010). Conversely in low permeability wall rocks fault zones can act as fluid conduits that focus flow; the faults studied here are in this latter category.

Fault zones exhibit extreme internal complexity and heterogeneous strain distribution (Wallace and Morris, 1986; Childs et al., 2009). They generally comprise one or more zones of fault rock (gouge, breccia, cataclasite) that bound or sit within a matrix of less sheared and highly fractured rock (Fig. 1). It has long been recognised that fault zones are irregular and can branch and anastomose over scales from millimetres to kilometres (Fig. 1) (Wallace and Morris, 1986; Caine et al., 1996; Childs et al., 1996a; Evans et al., 1997; Wibberley et al., 2008; Faulkner et al., 2010). Due to their geometric and kinematic complexity branch-lines between fault segments are often considered to be sites for enhanced along-fault flow (e.g., Cox, 1999).

The impact of fault zones on fluid flow within an area depends not only on their permeability relative to the wall rock but also on their size and connectivity (and the connectivity of elements within the zones) (Balberg et al., 1991; Evans et al., 1997; Cox, 1999). Large or highly connected faults or fault zones, with permeabilities which differ by at least two orders of magnitude from the host rock, have the greatest potential to modify flow (e.g., Bour and Davy, 1997;

* Corresponding author. GNS Science, PO Box 30368, Lower Hutt 5010, New Zealand.
E-mail addresses: h.seebeck@gns.cri.nz, hannuseebeck@gmail.com (H. Seebeck).
[1] Present address: GHD Christchurch, 226 Antigua Street, Christchurch 8011, New Zealand.

0191-8141/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2014.01.008

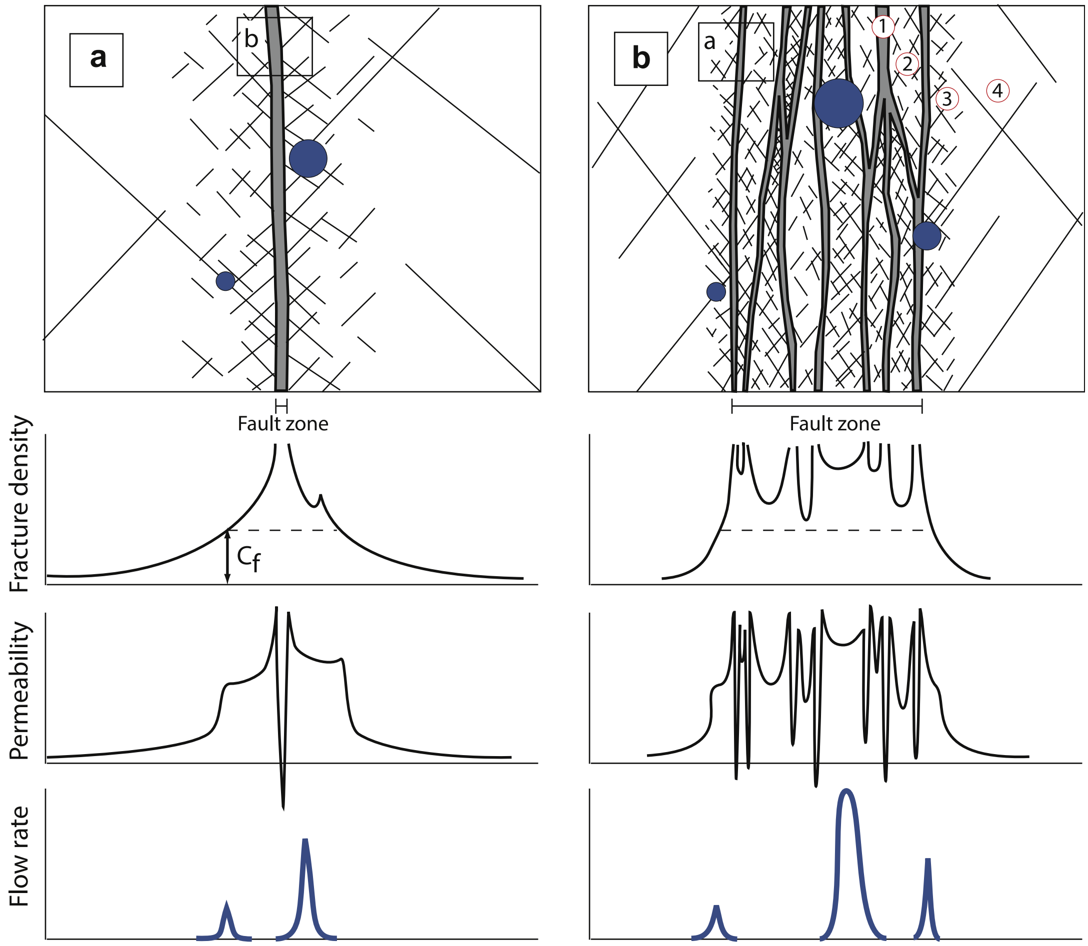

Fig. 1. Schematic hydrogeological properties of fault zone architecture (after Faulkner et al., 2010). (a) A single high strain slip zone surrounded by a lower strain damage zone (e.g. Chester and Logan, 1986). (b) Anastamosing pattern of multiple high strain slip zones bounding variably strained protolith (e.g. Wallace and Morris, 1986). The bulk physical properties of these two end-members is dependent on the scale of observation. A critical fracture density (Cf) is required before macro-scale permeability occurs. Fault zone architecture comprised four main elements; 1) Fault rock (gouge, breccia, cataclasite), 2) Fault bound lenses of variably strained wall rock, 3) Fractured wall rock and 4) Protolith. Filled blue circles indicate locations of water flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Evans et al., 1997; Sanderson and Zhang, 1999). In the context of petroleum and hydrogeology the extremely heterogeneous flow response of 'fracture reservoirs', i.e. those comprising conductive fractures in relatively tight rock (e.g. limestones), reflects the importance of fractures to fluid flow and the localisation of flow within them (Narr et al., 1996). For these types of reservoirs, much of the flow within individual wells can be within one or a small number of faults/fractures which are here referred to as the 'golden fracture'.

In this paper, we examine *in situ* fluid flow from tunnels through fault zones and protolith of low permeability (10^{-15}–10^{-17} m^2) Mesozoic greywacke basement and relatively permeable Miocene sandstone (10^{-15}–10^{-13} m^{-2}). The dataset includes information on fault geometries and their spatial relationships to water flowing into tunnels located along the margin of the Taupo Rift, New Zealand. Faults and water flow data from engineering geological logs and reports have been used to examine the factors influencing the rates and localisation of groundwater flows in relation to fault zone architecture and connectivity of the fault-fracture network. The strain distribution, permeability structure, and flow rates of basement and Miocene fault zones are highly heterogeneous, with fault zone thickness and flow rates exhibiting power-law distributions. As the prediction or location of high permeability pathways associated with fault zones will become increasingly important for the exploration and production of hydrocarbons (Manzocchi et al., 2010; Ilg et al., 2012), geothermal systems (Rosenburg et al., 2009) and CO_2 storage (Bretan et al., 2011), the results of this paper may have wide application.

2. Fault and fluid flow data

Fault geometry and fluid flow rate data were derived from 3 to 6 m diameter tunnels excavated ~100–500 m below the surface for the Tongariro Power Development project along the margins of the southern Taupo Rift, North Island, New Zealand (Fig. 2) (Beetham and Watters, 1985). The data were originally recorded on 1:240 engineering geological logs taken during excavation of the tunnels (1969–1981). The logs document rock properties, including strength, and water flow rate (Fig. 3) (Hegan, 1980) and constrain the first-order geometry, spatial distribution and fluid flow properties of fault zones over scales of centimetres to kilometres.

The dataset comprises 720 basement and 42 Miocene-Recent fault zones intersected by ~34 km of tunnels in Mesozoic greywacke basement and ~2.5 km through Miocene marine sandstone (Fig. 2) (Beetham and Watters, 1985; Townsend et al., 2008). Basement in the tunnels is indurated, Mesozoic deep water turbidites which have been subject to low-grade metamorphism (Beetham and Watters, 1985; Mortimer, 2004). These rocks have undergone multiple episodes of faulting and folding, including post 2 Ma northwest-southeast oriented extension of the Taupo Rift, with beds generally dipping steeply (>60°) and striking north-