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Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones

Agust Gudmundsson [a,*], Trine H. Simmenes [b,1], Belinda Larsen [b], Sonja L. Philipp [c]

[a] Department of Earth Sciences, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK
[b] Department of Earth Science, University of Bergen, Norway
[c] Geoscience Centre, University of Göttingen, Germany

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A B S T R A C T

The way that faults transport crustal fluids is important in many fields of earth sciences such as petroleum geology, geothermal research, volcanology, seismology, and hydrogeology. For understanding the permeability evolution and maintenance in a fault zone, its internal structure and associated local stresses and mechanical properties must be known. This follows because the permeability is primarily related to fracture propagation and their linking up into interconnected clusters in the fault zone. Here we show that a fault zone can be regarded as an elastic inclusion with mechanical properties that differ from those of the host rock. As a consequence, the fault zone modifies the associated regional stress field and develops its own local stress field which normally differs significantly, both as regard magnitude and orientation of the principal stresses, from the regional field. The local stress field, together with fault-rock heterogeneities and interfaces (discontinuities; fractures, contacts), determine fracture propagation, deflection (along discontinuities/interfaces), and arrest in the fault zone and, thereby, its permeability development. We provide new data on the internal structure of fault zones, in particular the fracture frequency in the damage zone as a function of distance from the fault core. New numerical models show that the local stress field inside a fault zone, modelled as an inclusion, differ significantly from those of the host rock, both as regards the magnitude and the directions of the principal stresses. Also, when the mechanical layering of the damage zone, due to variation in its fracture frequency, is considered, the numerical models show abrupt changes in local stresses not only between the core and the damage zone but also within the damage zone itself. Abrupt changes in local stresses within the fault zone generate barriers to fracture propagation and contribute to fracture deflection and/or arrest. Also, analytical solutions of the effects of material toughness (the critical energy release rate) of layers and their interfaces show that propagating fractures commonly become deflected into, and often arrested at, the interfaces. Generally, fractures propagating from a compliant (soft) layer towards a stiffer one tend to become deflected and arrested at the contact between the layers, whereas fractures propagating from a stiff layer towards a softer one tend to penetrate the contact. Thus, it is normally easier for fractures to propagate from the host rock into the damage zone than vice versa. Similarly, it is easier for fractures to propagate from the outer, stiffer parts of the damage zone to the inner, softer parts, and from the stiff host rock to the outer damage zone, than in the opposite directions. These conclusions contribute to increased understanding as to how fractures propagate and become arrested within fault zones, and how the fault zone thickness is confined at any particular time during its evolution.

1. Introduction

In recent years, there has been considerable geological work on the internal structure of major fault zones (e.g., Byerlee, 1993; Bruhn et al., 1994; Caine et al., 1996; Sibson, 1996; Evans et al., 1997; Gutmanis et al., 1998; Sibson, 2003; Gudmundsson, 2004; Shimamoto et al., 2004; Berg and Skar, 2005; Agosta and Aydin, 2006; Faulkner et al., 2006; Bradbury et al., 2007; Li and Malin, 2008). This work has partly focused on analysing the fault rocks themselves,

* Corresponding author.
E-mail addresses: a.gudmundsson@es.rhul.ac.uk, rock.fractures@googlemail.com (A. Gudmundsson).
[1] Present address: StatoilHydro Research Center, Sandsliveien 90, 5020 Bergen, Norway.

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Fig. 1. View west, two parallel fault zones seen as lineaments (marked by arrows) dissecting layers of limestone and shale in the Bristol Channel at Kilve, the Somerset Coast, England. The distance between the faults at the location of the arrows is about 25 m.

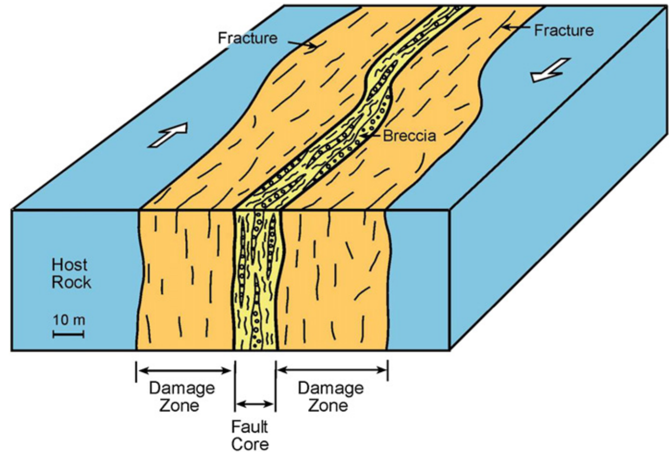

Fig. 2. Schematic illustration of a fault core and fault damage zone of a (strike-slip) fault. The core consists primarily of breccia and cataclastic rock (Fig. 3). The damage zone, located on each side of the core, commonly contains some cataclastic rocks and breccias but is characterised by numerous faults and fractures (Figs. 5 and 8), many of which are eventually filled with secondary minerals (Fig. 4).

their structure and mechanical properties, and partly on the permeability structure and its maintenance in fault zones. This is because of the importance that fluid transport by fault zones has in many fields of earth sciences. In particular, the in situ bulk hydraulic characteristics of fault zones have been measured in boreholes (e.g., Ahlbom and Smellie, 1991; Barton et al., 1995; Fisher et al., 1996; Braathen et al., 1999; Nativ et al., 1999; Lin et al., 2007; Tanaka et al., 2007) and modelled (e.g., Barton et al., 1995; Lopez and Smith, 1995; Bredehoeft, 1997; Faulkner et al., 2006; Healy, 2008; Li and Malin, 2008), the results suggesting that during non-slip periods the damage zone is the main conductor of fluids (cf. Gudmundsson, 2000; Gudmundsson et al., 2002).

Despite this work, the mechanical and permeability properties of major fault zones, including associated fracture propagation in the damage zone, are still not well understood, making it difficult to construct realistic numerical models. This is partly due to major fault zones being mechanically heterogeneous and, commonly, layered parallel with the fault plane. Thus, Young's modulus of a fault zone is likely to vary significantly with distance from the fault plane itself, that is, from the core and through the various subzones of the damage zone to the host rock (Gudmundsson, 2004; Gudmundsson and Brenner, 2003; Faulkner et al., 2006). As a consequence, fault zones tend to develop local stresses, many of which may be widely different from the associated regional stress fields (Gudmundsson and Brenner, 2003). Variations in local stresses are, in fact, universal features of mechanically layered rocks, whether the layering is parallel with the fault plane, and thus often steeply dipping or vertical, or gently dipping or horizontal as is many sedimentary basins and composite volcanoes (Gudmundsson, 2006; Gudmundsson and Philipp, 2006). In a fault zone, the local stress fields largely determine the fracture propagation and arrest, and associated seismic events, and thereby much of the fault-zone permeability.

This paper is on the internal mechanical structure of fault zones and how it affects local stresses, fracture development and arrest. The implications for fault-zone permeability are briefly discussed, but the focus is on the solid-mechanical aspects. In particular, the paper has three main aims. The first is to present results on the internal structure of fault zones and how they function as general elastic inclusions. The results derive from field studies of fault zones of various types. A second aim is to present new numerical models on the local stresses in fault zones. These models use field observations of internal structures of fault zones as a basis, focusing on the effects that different fracture frequencies have in generating subzones with different mechanical properties and local stresses within the main fault zones. The third aim is to explore the reasons why most fractures in fault zones remain short in comparison with the strike dimension of the fault zone itself. The explanation offered here is that the heterogeneous and anisotropic mechanical properties and local stresses within such fault zones, together with numerous interfaces/discontinuities (contacts, existing fractures), tend to deflect and, commonly, arrest most of the fractures after comparatively short propagation.

2. Internal structure of a fault zone

From a distance, fault zones appear as lineaments (Fig. 1). Indeed, fault zones are commonly viewed as lineaments with little or no internal structure and heterogeneity. As a consequence, fault zones have for a long time been modelled as single, elastic cracks or dislocations (Steketee, 1958; Press, 1965). While simple crack models can be very useful for understanding fault–fault interaction and fault effects on regional stresses, they are less useful for understanding the local stresses around and within the fault zone itself. Since these local stresses largely control the slip and fracture development and thus the permeability of the fault zone, the internal mechanical structure of the fault zone must be considered with a view of understanding its fluid-transport properties.

Detailed field observations of well-exposed fault zones show that they normally consist of two main structural units, namely a fault core and a fault damage zone (Fig. 2). The core takes up most of the fault displacement and it is also referred to as the fault slip zone (Bruhn et al., 1994; Sibson, 2003). Although the core contains many small faults and fractures, its characteristic features are breccias and cataclastic rocks. Commonly, the core rock is crushed and altered into a porous material (Fig. 3) that behaves as ductile or semi-brittle except at very high strain rates such as during seismogenic faulting. In the core, there are commonly numerous veins filled with secondary minerals spaced at centimetres or millimetres, that form dense networks. These networks, when transporting fluids, give the core a granular-media structure at the millimetre or centimetre scale, thereby supporting its being modelled as a porous medium.

While the field description in this paper of the fault core and damage zone focus on large fault zones, it should be emphasised