Earth-Science Reviews 152 (2016) 70–87

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Definition and classification of fault damage zones: A review and a new methodological approach

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ARTICLE INFO

Article history:
Received 30 May 2014
Received in revised form 6 November 2015
Accepted 7 November 2015
Available online 10 November 2015

Keywords:
Fault scaling relationship
Fault damage zone
Damage zone classification
Damage zone width
Cumulative fracture frequency

ABSTRACT

Although the widths of fault damage zones commonly show a positive correlation with displacements, these relationships also show a somewhat scattered distribution. We believe that one of the fundamental reasons for this problem is strongly related to subjective definitions and inconsistent uses of the term '*damage zone*'. Thus, firstly we classify damage zones into *along-fault*, *around-tip* and *cross-fault* damage zones based on descriptive views of an arbitrary fault exposure as well as their tridimensional locations around a segmented fault system. Secondly, we propose an advanced field technique and data acquisition method to more accurately define a damage zone using the distribution of cumulative fracture frequency. We tested this method on new field and borehole observations as well as previously published data to identify damage zone boundaries, and express them as a change in slope gradients of the cumulative distribution of deformation structures. The results show how this slope change can be a useful criterion in accurately defining the width of damage zones and some internal properties of fault zones. We argue that this damage zone classification and definition method should be adopted and used to prevent discrepancies in field data. This will help us to gain a better understanding of fault damage zone properties and their scaling with fault displacement.

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http://dx.doi.org/10.1016/j.earscirev.2015.11.006

1. Introduction

Brittle faults were traditionally considered to be single planar structures, but more recently they are described as complex volumetric zones composed of a variety of internal structures, such as slip surfaces, fault rock assemblages, and subsidiary deformation structures. Over the last few decades, a number of studies have focused on the fault zone architecture to understand fault evolution as well as its impact on fluid flow and mechanical behavior of the Earth's crust (Chester and Logan, 1986; Aydin and Schultz, 1990; McGrath and Davison, 1995; Caine et al., 1996; Childs et al., 1996, 2009; Peacock, 2002; Walsh et al., 2003; Kim et al., 2004; Shipton et al., 2006; Faulkner et al., 2010; Smith et al., 2013). In particular, it is well known that the damage zones, consisting of subsidiary structures through relatively large volume of rock surrounding the fault core, are associated with fault initiation, propagation and termination as well as its long-term evolution (Segall and Pollard, 1980; Cowie and Shipton, 1998; Peacock et al., 2000; Scholz, 2002; Pachell and Evans, 2002; Kim et al., 2003; Fossen, 2010; Gudmundsson et al., 2010). Damage zones are regarded as a key factor in a variety of geologic fields, such as the deformation processes associated with faulting (e.g. Chester et al., 1993; Schulz and Evans, 1998; Wilson et al., 2003), strain distribution and deformation history in a region (e.g. Scholz and Cowie, 1990; Walsh et al., 1991; Marrett and Allmendinger, 1992), earthquake rupture propagation and related seismic hazards (e.g. Sibson, 1989; Kim and Sanderson, 2008; Choi et al., 2012), and fluid permeability in the crust (Caine et al., 1996; Zhang and Sanderson, 1996; Childs et al., 1997; Evans et al., 1997; Townend and Zoback, 2000; Jourde et al., 2002; Shipton et al., 2002; Faulkner et al., 2003; Geraud et al., 2006; Kim and Sanderson, 2010). The last one is particularly important as it is used in practical applications to ground water (e.g. Lopez and Smith, 1995; Bense et al., 2008; Cilona et al., 2015), hydrocarbon reservoirs and ore-deposits (e.g. Aydin, 2000; Brogi, 2011; Rotevatn and Fossen, 2011), and the underground storage of CO_2 (e.g. Shipton et al., 2004; Dockrill and Shipton, 2010).

Damage zones have been described in terms of architecture and geometrical dimensions based on structural maps, field observations, and microstructural analysis (Chester et al., 1993, 2004; Antonellini and Aydin, 1994; Bruhn et al., 1994; McGrath and Davison, 1995; Schulz and Evans, 1998; Vermilye and Scholz, 1998; Storti et al., 2003; Billi et al., 2003; Micarelli et al., 2003; Di Toro and Pennacchioni, 2005; Agosta and Aydin, 2006; Johansen and Fossen, 2008; Riley et al., 2010; Bistacchi et al., 2011; Hausegger and Kurz, 2013; Lin and Yamashita, 2013; Smith et al., 2013; Walker et al., 2013). Damage zone architecture has been linked to slip accumulation and used in order to understand fault growth and evolution (Cowie and Shipton, 1998; Shipton and Cowie, 2001, 2003; Kim et al., 2003; Fossen et al., 2005; de Joussineau and Aydin, 2007; Childs et al., 2009). Numerous studies proposed fault evolution models using the scaling relationship between damage zone width and displacement (Evans, 1990; Scholz et al., 1993; Childs et al., 1996; Knott et al., 1996; Vermilye and Scholz, 1998; Beach et al., 1999; Fossen and Hesthammer, 2000; Shipton et al., 2006; Mitchell and Faulkner, 2009; Faulkner et al., 2011; Savage and Brodsky, 2011; Torabi and Berg, 2011). Although there is generally a broad positive correlation in this relationship, the collected data show a relatively scattered distribution. Several parameters, such as lithology and associated diagenesis, depth of faulting, tectonic environment, and deformation mechanism, have been suggested as responsible of the scattering (Evans, 1990; Childs et al., 1997; Fossen and Hesthammer, 2000; Shipton and Cowie, 2001; Di Toro and Pennacchioni, 2005; Shipton et al., 2006; Riley et al., 2010; Savage and Brodsky, 2011; Torabi and Berg, 2011). Whilst the suggested parameters could account for some factors in the data scattering, the fundamental reasons of data scattering are still poorly understood (e.g. Blenkinsop, 1989; Evans, 1990; Shipton et al., 2006; Faulkner et al., 2010).

In quantitative fault studies, variations in damage zone width may be induced by genetic and evolutionary properties of the damage zones. These properties include gradual, not drastic, changes in frequency of deformation structures (e.g. Shipton et al., 2006; Savage and Brodsky, 2011), the asymmetry between the hanging-wall and the footwall damage zone volumes (e.g. White et al., 1986; Knott et al., 1996; Aarland and Skjerven, 1998; Berg and Skar, 2005; de Joussineau and Aydin, 2007), and complex architectures related to multi-strands or braided fault cores (e.g. Childs et al., 1997; Faulkner et al., 2003, 2008, 2010). Uncertainties underlying this analysis may be more common on the large-scale faults, which are generally composed of a number of fault segments, because the above-mentioned factors can affect the geometric complexity of the fault zones in multiple ways.

Damage zone width, in general, has been defined by the frequency distribution of damage structures, such as cracks, fractures and deformation bands, which commonly decreases with distance from fault core (e.g. Chester and Logan, 1986; Smith et al., 1990; Scholz and Anders, 1994; Goddard and Evans, 1995). In other words, the external edge of the damage zones is generally displayed as the point at which the frequency of damage structures drops to a minimum or background level (Beach et al., 1999; Cello et al., 2001; Agosta and Kirschner, 2003; Berg and Skar, 2005; Faulkner et al., 2006; de Joussineau and Aydin, 2007; Mitchell and Faulkner, 2009; Gudmundsson et al., 2010; Riley et al., 2010). This method offers a useful tool for identifying damage zones, and hence has been broadly used in most of previous studies dealing with damage zone width. However, the criteria used to define the damage zone boundary have been varied in each field-measurement study, and these will be discussed in detail on Section 2. Inconsistent calculations of damage zone width, therefore, may in part come from ambiguity and/or subjectivity of the definition and measurement of damage zone, regardless of its genetic properties.

Furthermore, and perhaps most importantly, as faults are rarely completely exposed in 3-D, interpreting the 3-D distribution of damage zones is always challenging. These incomplete observations of fault zones have led to two slightly different uses of the term '*damage zone*' in modern structural geology (e.g. Schultz and Fossen, 2008; Kim and Sanderson, 2010). The first, which is the more extensively used in a cross-section of the fault zone, is referring to a highly deformed zone on both sides of the fault core (Chester and Logan, 1986; Ben-Zion and Malin, 1991; Caine et al., 1996; Billi et al., 2003; Odling et al., 2004; Bullock et al., 2014). The other use is for local clusters of subsidiary structures along fault traces, especially at fault step-overs and tips (Peacock and Sanderson, 1994; McGrath and Davison, 1995; Kim et al., 2000, 2003, 2004; Flodin and Aydin, 2004; Zhang et al., 2008). Note that these different uses are only related to the differences in descriptive views of a fault zone, not physical and/or mechanical characteristics of damage structures, and can cause an uncertainty to conduct a comprehensive and/or comparative study of the damage zones. Some researchers have mentioned that these terminological inconsistencies on estimating damage zone width could be a major cause of data uncertainty in scaling relationships between damage zone width and displacement (e.g. Shipton et al., 2006; Childs et al., 2009).

We argue that damage zone terminology should be clearly defined and classified based on clear criteria to help improve our understanding