Journal of Structural Geology 48 (2013) 85–94

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

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

Statistical tests of scaling relationships for geologic structures

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ARTICLE INFO

Article history:
Received 9 March 2012
Received in revised form
10 December 2012
Accepted 11 December 2012
Available online 4 January 2013

Keywords:
Scaling
Faulting
Displacement–length scaling
Deformation bands
Compaction bands

ABSTRACT

Displacement–length data from dilatant fractures (joints, veins, igneous dikes) and several varieties of deformation bands were analyzed statistically to investigate the applicability of mechanical models proposed for their formation. All 17 datasets are generally consistent with equilibrium or long-term power-law slopes on the displacement–length diagram of either 1.0 or 0.5. Similar to many faults, disaggregation deformation bands are consistent with a power-law scaling relation having a slope of approximately $c = 1$, implying a linear dependence of maximum displacement and discontinuity length ($D_{max} = \gamma L$). In contrast, dilatant fractures, cataclastic deformation bands, and shear-enhanced compaction bands are consistent with a power-law scaling relation with a slope of approximately $c = 0.5$, implying a dependence of maximum displacement on the square root of length ($D_{max} = \alpha L^{1/2}$). The scaling relations represent an average, or long-term equilibrium outcome of deformation for conditions such as length-scale, time-scale, temperature, chemistry, and an effectively homogeneous far-field stress field, allowing for variations such as rapid and/or localized behaviors. The displacement–length scaling of these geologic structures follows systematic relationships that provide information on host-rock properties and the physics of fracture and deformation-band propagation.

1. Introduction

The basic mechanical controls on the propagation and growth of a wide range of geologic structures, including joints, faults, veins, dikes, and deformation bands, can be investigated and understood by statistical analysis of the geometric attributes of the populations of the structures. These structures develop during progressive strain localization with many key characteristics showing general scaling relationships over some particular set of conditions such as length-scale. The scaling relations are interpreted to describe an average, or long-term equilibrium value, with departures resulting from processes occurring over shorter timescales and particular spatial scales (e.g., Kim et al., 2004). Numerous studies in the literature suggest that a subset of variables exert a primary influence on the scaling; length and displacement appear to collectively capture the main aspects of loading conditions, strain accumulation during structural development, and evolving rock properties. The empirical data can then be used to test the scaling predictions of theoretical models for the growth of the geologic structures.

A fault can be described as a sharp structural discontinuity, defined in three dimensions by its slip surfaces and related structures including fault core, secondary structures, and damage zones that formed at any stage or location in the evolution of the structure. Ductile deformation structures such as drag or faulted fault-propagation folds are sometimes included in the definition along with clay smearing or other early forms of strain localization (e.g., Kim et al., 2004; Schultz and Fossen, 2008). Despite this rather comprehensive description, many studies have however demonstrated the existence of basic scaling relationships for faults, including displacement vs. length (e.g., Kim and Sanderson, 2005), fault-zone thickness vs. displacement (e.g., Childs et al., 2009; Aydin and Berryman, 2010), stepover geometry (separation vs. overlap; Aydin and Nur, 1982; Soliva and Benedicto, 2004; de Joussineau and Aydin, 2009; Long and Imber, 2011), and displacement vs. segmentation (Wesnousky, 1988; de Joussineau and Aydin,

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http://dx.doi.org/10.1016/j.jsg.2012.12.005

2009). Comparable scaling relations have been identified for opening-mode structures, such as joints, veins, and dikes (e.g., Olson, 2003) and deformation bands (e.g., Fossen et al., 2007; Tembe et al., 2008; Ballas et al., 2012; Schultz and Soliva, 2012; Tondi et al., 2012; Soliva et al., in press).

Values for the maximum displacements D_{max} (i.e., shear offset) and horizontal lengths L of faults can be related for the long-term, equilibrium case by $D_{max} = \gamma L^c$, with c for fault populations commonly being in the approximate range of 1.0 (e.g., Cowie and Scholz, 1992a; Clark and Cox, 1996; Bailey et al., 2005; Twiss and Marrett, 2010). Fault populations can define an approximately linear dependence of maximum shear displacement and discontinuity length ($D_{max} = \gamma L$) with γ dependent on several factors, including host-rock stiffness and shear driving stress (e.g., Cowie and Scholz, 1992a; Gudmundsson, 2004; Scholz, 2002, p. 116; Schultz et al., 2006). However, these power-law scaling relations require certain conditions including effectively homogeneous far-field stress fields. Departures from these ideal conditions, such as stratigraphic or mechanical layering in which structures are initially growing, can lead to transient or local scaling relations such as non-linear displacement–length scaling, exponential length or displacement systematics, and uniform spacing. Such transient or local departures from the long-term, equilibrium power-law scaling relation are related to processes such as growth by segment linkage (Cartwright et al., 1995) and stratigraphic restriction (Soliva et al., 2005). Fault scaling relations thus represent fundamental relationships in structural geology and rock mechanics, conceptually paralleling Byerlee's rule for frictional sliding (e.g., Kohlstedt et al., 1995).

Although the scaling of dilatant structures is well recognized, its quantification and interpretation also remain somewhat controversial. Early work by Vermilye and Scholz (1995) suggested that veins (Bons et al., 2012) and igneous dikes (Rubin, 1995) scale, in the long-term or equilibrium sense, as $c = 1$, similar to faults. However, Olson (2003) proposed a theoretical model based on linear elastic fracture mechanics (LEFM) that predicted square root scaling to be dominant in opening-mode fractures. Re-analysis of a subset of the Vermilye and Scholz (1995) data as well as igneous dike data (Delaney and Pollard, 1981) showed that many veins and dikes are better described to scale approximately as $c = 0.5$ instead ($D_{max} = \alpha L^{1/2}$, where D_{max} is the maximum kinematic aperture), which is consistent with growth under conditions of constant near-tip rock properties (i.e. a critical opening-mode stress intensity factor, K_{Ic}). After publication of Olson's (2003) paper, more datasets for dilatant structures became available (see compilations by Klimczak et al., 2010 and Schultz et al., 2010). This interpretation of sub-linear scaling has been challenged by Scholz (2010, 2011), who advocated a linear scaling relation (i.e., $c = 1.0$) for dilatant fractures, similar to the scaling of faults (see Olson and Schultz, 2011 for discussion). The continuing controversy about the scaling of dilatant structures motivates a statistical assessment of their scaling properties.

Displacement–length data are also available for three varieties of deformation bands: disaggregation bands, cataclastic shear deformation bands, and shear-enhanced compaction bands. Disaggregation bands are non-cataclastic and form by shear localization in sediments and poorly consolidated sedimentary rocks with negligible volume change within the bands (e.g., Fossen, 2010; Brandes and Tanner, 2012). Cataclastic shear deformation bands are shear localization structures along which band-parallel shear displacement (typically 1–3 cm) is accompanied by a much smaller band-normal compaction that is usually a fraction of a millimeter and related to porosity reduction within the bands (e.g., Fossen et al., 2007). These bands are termed cataclastic shear bands in this paper for simplicity. Shear-enhanced compaction bands may also involve some cataclasis and grain-contact dissolution in addition to porosity reduction by grain reorganization. For these bands, the magnitude of volumetric offset is considered to be comparable to, or somewhat less than, the shear offset (e.g., Eichhubl et al., 2010; Schultz and Soliva, 2012; Soliva et al., in press).

The scaling of dilatant fractures or cataclastic shear deformation bands that both accommodate some degree of volumetric change across them was suggested to be consistent with equilibrium or long-term power-law slopes of approximately 0.5 by various workers, including Fossen and Hesthammer (1997), Rudnicki et al. (2006), Fossen et al. (2007), Rudnicki (2007), Tembe et al. (2008), Schultz et al. (2008a, 2010), and Schultz and Soliva (2012). One interpretation of this scaling relation involves propagation and growth of deformation bands at a critical value of stress intensity factor combined with appropriate remote loading conditions in a manner similar to opening-mode structures (e.g., Olson, 2003). Another interpretation invokes band thickening during propagation with only modest, non-singular stress changes at band tips (Chemenda, 2011). A definitive empirical assessment of the equilibrium scaling relation for dilatant fractures and deformation bands could inform a discussion of the primary factors controlling their propagation and growth.

In this paper, we statistically evaluate displacement–length data for three varieties of opening-mode fractures (joints, veins, igneous dikes) and three varieties of deformation bands (cataclastic shear bands, disaggregation bands, and shear-enhanced compaction bands). We use the approach employed by Clark and Cox (1996) in their study of faults and discuss the implications for the growth and scaling of these common non-fault structures.

2. Approach

Displacement–length data were compiled from several sources (Fig. 1), including 10 datasets for dilatant fractures compiled by Klimczak et al. (2010) and Schultz et al. (2010), and 7 datasets for deformation bands. The deformation band datasets include two for cataclastic shear deformation bands (Fossen and Hesthammer, 1997; Wibberley et al., 2000); three for disaggregation bands, in which no cataclasis or volumetric strain is apparent (Wibberley et al., 1999; Fossen, 2010; and Exner and Grasemann, 2010); and two for shear-enhanced compaction bands (Sternlof et al., 2005; Schultz, 2009; Schultz and Soliva, 2012) (Table 1).

The data for these types of geologic structures exhibit scatter due to several factors that are well known to contribute to scatter in datasets for fault populations (e.g. Cowie and Scholz, 1992b; Schultz, 1999; Crider and Peacock, 2004), including mechanical interaction (Renshaw and Park, 1997; Olson, 2003), three-dimensional shape (Willemse et al., 1996; Schultz and Fossen, 2002), stratigraphic restriction (Nicol et al., 1996; Soliva et al., 2005; Soliva and Schultz, 2008), and measurement technique (e.g., Clark and Cox, 1996; Xu et al., 2005). An assessment of the quality of displacement–length measurements for these data sets is given in Appendix A. In general, the datasets are of sufficiently good quality and internal consistency for statistical analysis although variability exists in the level of documentation for measurement technique and uncertainties.

As noted by many including Cowie and Roberts (2001), no geologic structure is truly isolated from its neighbors, because fractures and deformation bands form and develop as part of a population and because their presence also changes the stiffness of the surrounding rock (e.g., Kachanov, 1992; Olson, 2003). The effect of fault or joint interaction on the scaling relations was investigated quantitatively by Willemse et al. (1996), Willemse (1997), and Olson (2003). Interaction contributes to increased scatter in the scaling relations (Xu et al., 2005), with the increased or decreased