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# Dependence of displacement–length scaling relations for fractures and deformation bands on the volumetric changes across them

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ABSTRACT

Displacement–length data from faults, joints, veins, igneous dikes, shear deformation bands, and compaction bands define two groups. The first group, having a power-law scaling relation with a slope of $n = 1$ and therefore a linear dependence of maximum displacement and discontinuity length ($D_{max} = \gamma L$), comprises faults and shear (non-compactional or non-dilational) deformation bands. These shearing-mode structures, having shearing strains that predominate over volumetric strains across them, grow under conditions of constant driving stress, with the magnitude of near-tip stress on the same order as the rock's yield strength in shear. The second group, having a power-law scaling relation with a slope of $n = 0.5$ and therefore a dependence of maximum displacement on the square root of discontinuity length ($D_{max} = \alpha L^{0.5}$), comprises joints, veins, igneous dikes, cataclastic deformation bands, and compaction bands. These opening- and closing-mode structures grow under conditions of constant fracture toughness, implying significant amplification of near-tip stress within a zone of small-scale yielding at the discontinuity tip. Volumetric changes accommodated by grain fragmentation, and thus control of propagation by the rock's fracture toughness, are associated with scaling of predominantly dilational and compactional structures with an exponent of $n = 0.5$.



## 1. Introduction

Displacement–length ($D$–$L$) scaling relations for faults and other common geologic structures provide a window into the mechanics of brittle strain localization in compact and porous rocks. $D$–$L$ scaling relations of faults are well understood, yielding information on the mechanics of localized shear deformation. Maximum displacement $D_{max}$ and horizontal fault length $L$ are related by $D_{max} = \gamma L^n$, with $n$ for fault populations generally being in the range of 1.0 (e.g. Cowie and Scholz, 1992a; Clark and Cox, 1996; Scholz, 2002; Xu et al., 2005). Neglecting the influence of short-range mechanical interaction and other effects, fault populations therefore generally define a linear dependence of maximum displacement and discontinuity length ($D_{max} = \gamma L$). In contrast, the scaling of dilatant structures has been less clear. Early work by Vermilye and Scholz (1995) suggested that veins and igneous dikes scale as $n = 1$, similar to faults. However, re-analysis by Olson (2003) showed that those veins and dikes scale as $n = 0.5$ ($D_{max} = \alpha L^{0.5}$), consistent with growth under conditions of constant rock properties (i.e. the opening-mode fracture toughness, $K_{Ic}$) instead of constant driving stress (that is a function of friction and normal stress, as in the case of faults; e.g. Scholz, 2002, p. 116). With displacement–length data now available for joints and three varieties of deformation bands including compaction bands, a more comprehensive investigation of the scaling relations for all three kinematic types of structures (opening, shearing, and closing) and both discontinuity classes (sharp vs. tabular; Aydin et al., 2006; Schultz and Fossen, 2008) is now possible.

In this paper we compile and present displacement–length data for the various types of geologic structural discontinuities, including faults, joints, veins, igneous dikes, shear deformation bands, and compaction bands. We then show how the slopes and intercepts of the associated scaling laws contain physical information on the mechanics and propagation of these common structures.

## 2. Data compilation

Measurements of displacement–length data from the literature for the principal types of geologic structural discontinuities

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(Schultz and Fossen, 2008) are presented in Figs. 1–4. The data shown exhibit an intrinsic scatter due to several factors (e.g. Schultz, 1999) including mechanical interaction, three-dimensional shape (Willemse et al., 1996; Schultz and Fossen, 2002), and where along the structure's surface the displacement was measured (e.g. Xu et al., 2005), but following standard practice (e.g. Clark and Cox, 1996) the data are compared collectively by calculating or using values of maximum displacement. In all diagrams the axis ranges and labels are consistent, facilitating comparisons between the different types of structures.

The data for faults are compiled and presented in Fig. 1. Fault populations are seen in the figure to scale linearly in displacement and length (Cowie and Scholz, 1992a; Xu et al., 2005; dotted lines in Fig. 2), with the proportionality $\gamma$ ranging between $10^{-1}$ and $10^{-3}$ for the full data set and with smaller ranges of $\gamma$ for individual fault populations within the same lithology and tectonic environment (Clark and Cox, 1996; Schultz et al., 2006).

Six data sets for joints, veins, and igneous dikes are shown in Fig. 2, with the three new data sets not investigated by Olson (2003) shown with regression lines in bold. These new measurements double the number of dike data sets, increase the number of data sets for veins, and add a data set for joints, which were previously not represented, to the database compiled and shown in the figure. As evident in Fig. 2, opening-mode structures plot with distributions more consistent with $L^{0.5}$ (dashed lines in Fig. 2) than with linear scaling (dotted lines in Fig. 2), implying a different physical control on their scaling relations than is the case for faults.

Several data sets are now available for deformation bands (Fossen et al., 2007). The cataclastic compactional shear deformation bands measured by Fossen and Hesthammer (1997) and a second data set for these structures reported by Wibberley et al. (2000) scale approximately as $n = 0.5$ (Fig. 3, filled triangles). Two data sets for disaggregation deformation bands for which volumetric strains appear to be negligible, compiled by Fossen et al. (2007), and one for slip surfaces in low-porosity sandstone and described in the Appendix, exhibit steeper slopes close to $n = 1.0$ (Fig. 3).

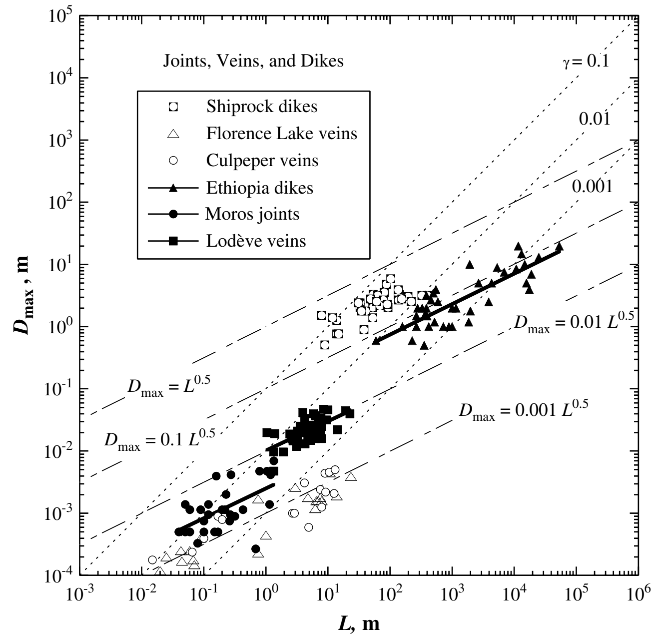


**Fig. 2.** Compilation of joints, veins, and dikes; see Olson (2003), the Appendix, and the text for sources of data and discussion. Lines of constant slope are shown: $n = 1$, dotted, as in Fig. 1; $n = 0.5$, dashed. Heavy lines show power-law fits to the data sets not analyzed by Olson (2003). Ethiopia dikes: $D_{max} = 0.078L^{0.49}$, $r^2 = 0.66$; Moros' joints: $D_{max} = 0.0025L^{0.48}$, $r^2 = 0.45$; Lodève sparitic sinuous veins: $D_{max} = 0.01L^{0.47}$, $r^2 = 0.41$.

The final plot shows the scaling relations for compaction bands in sandstone, represented by data from the two currently known localities (Mollema and Antonellini, 1996; Sternlof et al., 2005; Schultz, in press). Compaction bands are a variety of deformation band that accommodates contractional normal strain with little or no shear strain across the band (Mollema and Antonellini, 1996; Sternlof et al., 2005; Schultz and Siddharthan, 2005; Aydin et al., 2006; Holcomb et al., 2007; Schultz and Fossen, 2008). The data

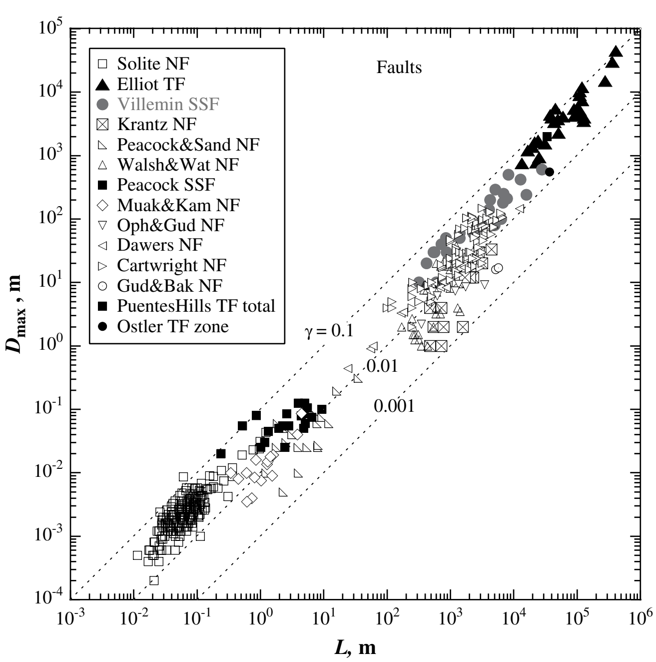


**Fig. 1.** Compilation of faults; see Cowie and Scholz (1992a), Schlische et al. (1996), and Schultz et al. (2006) for sources of data and discussion. Normal faults (NF), open symbols; strike-slip faults (SSF), gray symbols; thrust faults (TF), filled symbols. Lines of constant slope are shown: $n = 1$, dotted, with $D/L = \gamma$.

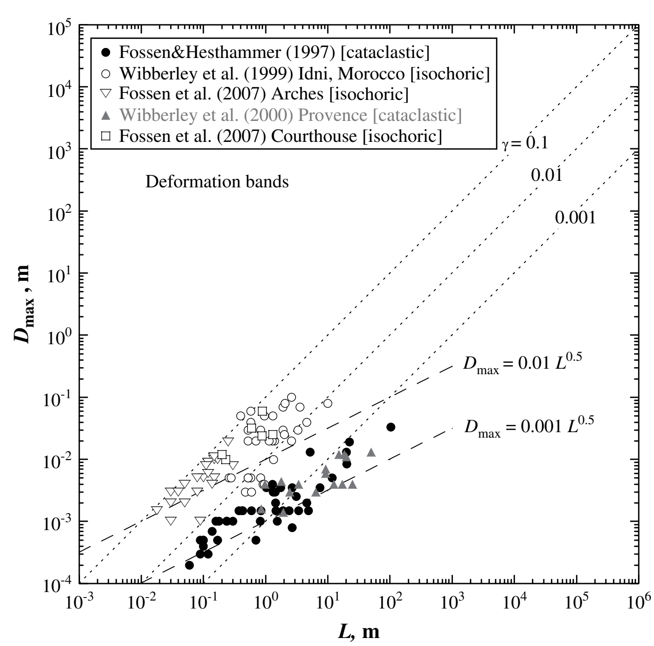


**Fig. 3.** Compilation of deformation bands; see Fossen and Hesthammer (1997), Fossen et al. (2007), and the Appendix for sources of data and discussion. Cataclastic bands, filled circles and triangles; isochoric shear bands, open symbols. Lines as in Fig. 2.