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SHORT NOTE

Thickness–displacement relationships for deformation zones

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Abstract—Empirical relationships between thickness and displacement for different types of deformation zones in quartzofeldspathic rocks are presented. Faults exhibit a linear correlation of thickness with displacement and an average displacement/thickness ratio of 63; mylonite zones may show a similar correlation (with an average ratio of 2), though the data are problematic. The thickness–displacement relationships provide information on the growth of deformation zones with time and the role of strain softening and hardening during progressive displacement.

INTRODUCTION

LARGE and small deformation zones are often found together; however, the relationship among coeval sets of zones present on different length scales is usually obscure. Do large deformation zones grow from smaller ones? Under what conditions do deformation zones widen or thin with time? Despite much work on the geometry and internal structure of deformation zones, their growth and scaling is still poorly understood (Watterson 1979, 1986, Sorensen 1983). By considering deformation zones with a wide range of sizes, scaling laws based on the relationships among different morphometric and geometric parameters can be defined (Scholz 1982). The approach taken in this short note is to examine the empirical relationship between thickness (T) and displacement (D) for different types of natural deformation zones. This approach parallels that of Ranalli (1977) and Watterson (1986), who studied the relationship between displacement and trace length or 'width' (long axis of the tip loop) of faults.

I have compiled thickness–displacement data for two groups of natural deformation zones, recognized by their dominant type of high-strain tectonite: cataclasites (produced by brittle fracture) and mylonites (dominated by intracrystalline plasticity). Diagnostic microstructural and textural criteria are well documented for these two groups, though the subdivision is somewhat arbitrary, as both transitional and composite deformation zones are included (e.g. Mitra 1978, 1984). The deformation zones are restricted to quartzofeldspathic protoliths (with few exceptions) to avoid introducing lithology as a variable (Aydin 1978, Robertson 1983). The linear regression parameters describing the relationship between thickness and displacement for the two groups of deformation zones are given in Table 1. Regression parameters for Scottish pseudotachylites (Sibson 1975) are also given in this table.

Table 1. Linear regression parameters of log thickness (T) vs log displacement (D) for three types of deformation zones. The power law relationship has the form $D = bT^a$. N = number of measurements, a = exponent (slope), b = pre-exponent (antilog of the intercept), r = Pearson's correlation coefficient

Type of deformation zone	N	a	b	r
Cataclasites	113	0.97	63	0.97
Mylonites	49	1.03	2.1	0.99
Scottish pseudotachylites	14	1.73	7277	0.94

NATURAL DEFORMATION ZONES

Thickness–displacement data for brittle deformation zones (BDZ), both natural and experimental, were first compiled by Otsuki (1978) and Robertson (1982). Their compilations (of natural BDZ only) have been combined and expanded with the addition of more recent data (Fig. 1). Displacements on these faults were usually determined by an offset marker measured in the plane containing the net-slip lineation, or more rarely, by an offset piercing point. BDZ in general exhibit a remark-

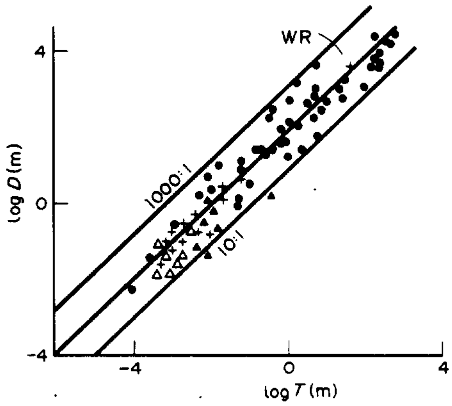

Fig. 1. Log–log plot of thickness T vs displacement D (m) for brittle deformation zones. Lines with 45° slopes give constant thickness/slip ratios. The filled triangles are from the Sierra Nevada (Segall & Pollard 1983a, Segall & Simpson 1986), and the pluses are from semi-consolidated rocks in Japan (Otsuki 1978). WR is the White Rock Thrust (Mitra *et al.* in press). This figure also includes data from Robertson (1983) and Fletcher & Gay (1971), as well as New Jersey (open triangles).

ably strong, positive correlation between thickness and displacement: the new regression parameters (Table 1) for 113 BDZ are similar to the parameters obtained from Otsuki's (1978) and Robertson's (1983) data. The exponent of 0.97 suggests a near linear relationship over seven orders of magnitude in size. However, given the large variance, the data could fit non-linear functions. The *D/T* ratio (mean = 63) does not change systematically with size, though ratios vary by at least two orders of magnitude (between 10 and 1000), with the variance increasing slightly with increasing size of the BDZ (a heteroscedastic distribution). As Robertson (1983) notes, both thickness and displacement are difficult to measure for large faults; the actual thicknesses may be exaggerated by inclusion of large, less-deformed augen, for example.

Data for a single population of small epidote- or chlorite-rich BDZ cutting Grenville gneisses in New Jersey, U.S.A. (Hull *et al.* 1986), are also shown in Fig. 1. Fracturing of feldspars, quartz and hornblende in the New Jersey BDZ has led to appreciable grain-size reduction (10s to 100s of microns), even in zones a few millimeters thick. Breccias and microbreccias grade into thoroughly indurated gouge associated with corrugated slickensides (sliding surfaces) that are found along one or both boundaries and within the BDZ; an unknown proportion of the displacement may be accommodated by these sliding surfaces (Aydin & Johnson 1978). The New Jersey population shows a positive correlation between thickness and displacement, as do many other BDZ populations (Aydin & Johnson 1978, Otsuki 1978, Robertson 1983, Segall & Pollard 1983a; contrast with Jamison & Stearns 1982, Blenkinsop & Rutter 1986). More importantly, *individual* BDZ from New Jersey also show the same positive correlation, albeit much more poorly defined and over limited fault trace exposures (<20 m).

Some of the scatter seen in Fig. 1 may be due to variation in lithology and normal stress, as suggested by Robertson (1983), in addition to uncertainties in the field measurements. Scholz (1987) has derived a model based on wear theory that predicts a linear relationship between displacement and thickness for constant values of hardness and normal stress; increasing hardness or decreasing normal stress will raise the *D/T* ratio in Scholz's model. This model does not take into account other mechanisms of grain-size reduction, such as subcritical crack propagation under low stress conditions, which may yield other *D–T* relationships.

Thickness–slip data for 49 low- to high-grade, quasi-plastic to mylonitic deformation zones have been compiled from a number of sources (Fig. 2). Displacement on almost all of these zones was calculated using the simple-shear assumption and deflected markers or foliation. A few mylonite zones do have independent checks on net slip (Mitra 1979, Sorensen 1983), which corroborate the results of strain integration. The mylonitic zones also show a positive linear relationship (Table 1) between thickness and slip over eight orders of magnitude of size. The positive relationship is expected, as

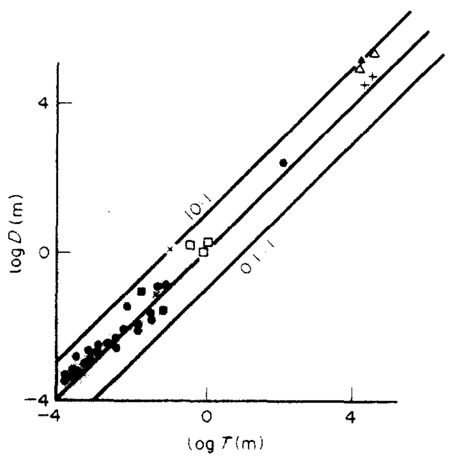

Fig. 2. Log–log *T–D* plot (m) for mylonite zones. Quasi-plastic zones from the Virginia Blue Ridge (Mitra 1979) are dots. Moderate- to high-grade zones from the Maggia Nappe (open squares, Ramsay & Allison 1979; filled squares, Simpson 1983), West Greenland (open triangles, Bak *et al.* 1975; filled triangle, Sorensen 1983), Castell O'Dair (×, Ramsay & Graham 1970) and the Limpopo (+, Coward *et al.* 1973) are also shown. All displacements in this figure are calculated from integrated shear strains (see text).

thickness is actually plotted against $T\bar{\gamma}$, rather than independently measured displacement. The regression suggests a best fit $\bar{\gamma}$ of 2, as found by Mitra (1979) for a slightly smaller data set, with $\bar{\gamma}$ varying from about 1 to 10.

These low values may seem surprising at first, but most of the mylonitic zones have relatively broad, low-strain shoulders (see Ingles 1986). In addition, the data are biased against high-strain zones in which the foliation is essentially parallel to the deformation zone boundaries; $\gamma = 10$ is the approximate upper limit of resolution of shear strain by the rotated foliation method. There are other problems with the mylonite data. Ductile deformation zones with an apparent simple-shear geometry can form by a variety of strain histories other than plane-strain simple shear (Bell 1981, Simpson 1981). Indeed, a perusal of the strain literature reveals that many mylonite zones lack plane finite strains that cannot be accounted for by volume changes or other mechanisms.

There are few *D–T* data for other types of high-strain tectonites, such as ultramylonites and pseudotachylites, which might show different mechanical behavior (Fig. 3). Gilotti & Kumpulainen (1986) have described a thin zone (10–100 m) of greenschist-facies ultramylonites and mylonites along the Särv Thrust in Scandinavia. Displacement on the Särv has been estimated at 100 km (Hossack 1983), indicating a *D/T* ratio of 10^3–10^4, consistent with $\gamma = 10^3$–10^4 calculated from thinned dolerite dikes (assuming simple shear) in the deformation zone (Gilotti in preparation). The Glarus Thrust (Schmid 1975) contains about 1 m of Lochseiten calcmylonite that deformed superplastically with a large component of grain-boundary sliding (Schmid *et al.* 1977). Slip on the Glarus has been estimated at 40 km, corresponding to a *D/T* ratio of 10^4–10^5. Upper and lower bounds for displacement on ultramylonite zones in Archean metagraywackes (Hull 1984) have been esti-

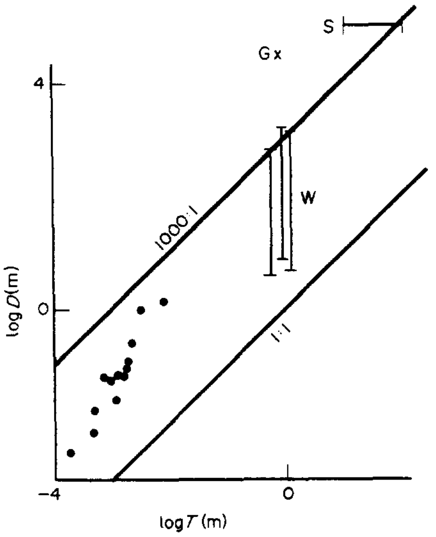

Fig. 3. Log–log T–D plot (m) for other high-strain zones. Data from pseudotachylite zones in the Outer Hebrides (dots; Sibson 1975) and ultramylonite zones from the Glarus (G; Schmid 1975), Särv (S; Gilotti & Kumpulainen 1986) and Wyoming (W; Hull 1984) are plotted.

mated using the lengths of the zones and integrated shear strain; estimates of D/T range from 10^2 to 10^3. Although the data are quite limited, ultramylonite zones apparently display higher $\bar{\gamma}$ (assuming simple shear) than cataclastic or mylonitic zones.

Sibson (1975) measured thicknesses and separations for small, pseudotachylite-bearing fault zones cutting Lewisian gneiss in the Outer Hebrides (Fig. 3). Net slip lineations are absent, so actual displacements were not attainable, and because of the extreme ductility of the pseudotachylite, which can flow out of or into the fault zones, there is also some uncertainty in the true thicknesses. Nonetheless, separation and thickness are strongly correlated (Table 1, Sibson 1975) and non-linear; the large exponent (1.73) indicates that D/T increases rapidly with increasing size of the zone. In its non-linear D–T relationship, the Scottish pseudotachylites contrast with both the cataclasites and mylonites.

SHEAR-ZONE CLASSIFICATION

Simple-shear zones can be classified by their change in thickness as a function of time, as suggested by Means (1984). A Type 1 zone widens with time (Fig. 4a) as the zone strain hardens; the interior of the zone may reach some limiting value of γ or the interior may continue to accumulate strain as strain rate decreases. Strain hardening is associated with grain-size reduction in cataclasites, as higher stresses are required to propagate transgranular (unstable) fractures (Petch 1953, Mitra 1978). Dilatant fluid-saturated cataclasites may strain harden when volumetric expansion due to cracking is faster than the pore filling rate (Rudnicki 1984). Conversely, porosity reduction in cataclasites by close packing of unsorted breccia (Dunn *et al.* 1973, Aydin 1978) and by neomineralization or cementation (Blenkinsop & Rutter 1986) can also produce work hardening. In addition to the mechanical behavior of the tectonites, certain 'boundary conditions' might produce hardening; propagation will be impeded at deformation zone intersections or by lateral changes in lithology (to harder rocks).

Profiles of angular shear strain across a Type 1 zone with a limiting value of strain will show a characteristic flat top. Flat-topped strain profiles (determined by rotated foliation) have been noted in some mylonite zones (Ramsay & Graham 1970, Watterson 1979, Sorensen 1983); however in these examples, the constant strains simply reflect constant orientation of foliation at low angles to the deformation-zone boundary. Large variations in shear strain, produced by small deviations in foliation orientation, might go unrecognized. A Type 1 zone exhibits a positive correlation between thickness and displacement.

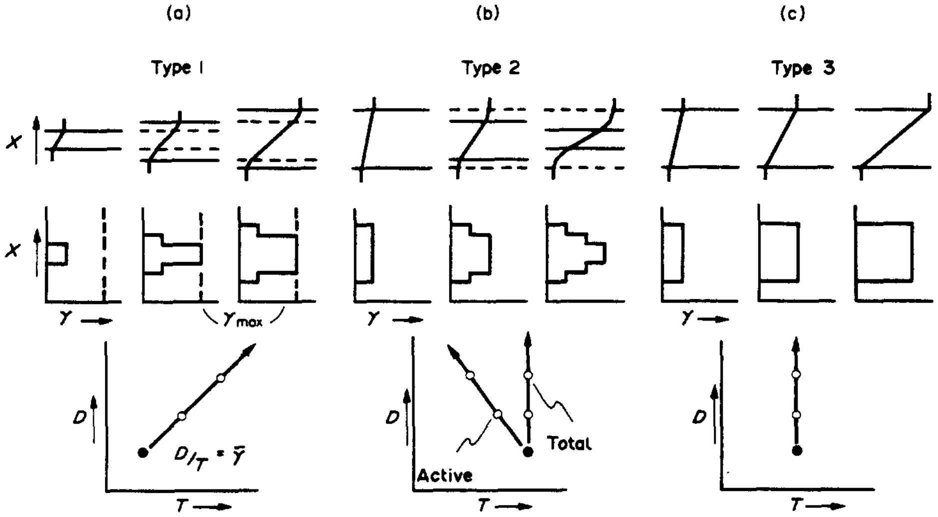

Fig. 4. (a) A Type 1 (widening) simple-shear zone at three different times, showing the corresponding shear strain profiles and thickness–displacement plot. γ_{max} is the limiting shear strain. The slope of the T–D curve is the average shear strain. (b) A Type 2 (thinning) shear zone. This zone is strain hardening on the margins. The T–D plot compares the total width of the zone with just the 'active' portion. (c) A Type 3 (constant thickness) shear zone.

A Type 2 zone decreases in thickness with time (Fig. 4b). There are several mechanisms for thinning the active portion of a shear zone. An initial perturbation in the rate-controlling variables across the zone might produce continuous or run-away strain softening, localizing the deformation. Softening mechanisms have been summarized by Cobbold (1977) and White *et al.* (1980). Alternatively, portions of the zone may decelerate, producing an ever-shrinking active zone; work hardening on the shear-zone boundaries might propagate towards the center, for example. Regardless of the specific shrinking mechanism, profiles across Type 2 zones will exhibit sharp peaks of γ, which are commonly seen (e.g. Ramsay & Graham 1970, Simpson 1983). The slope of the D–T curve for an individual Type 2 zone will be infinite if the total thickness of the zone is considered and negative if only the high strain, 'active', portion is measured.

Though not considered by Means (1984), the thickness of a Type 3 simple shear zone does not change with time (Fig. 4c), perhaps reflecting constant strain rate or true steady-state deformation. Another kind of Type 3 zone is mechanically constrained, with a softer layer imbedded between two very stiff members. Shear-strain profiles at different times along a Type 3 zone will exhibit flat tops and uniform strains, similar to Type 1 zones. The D–T relationship for a single zone will be similar to Type 2, constant thickness regardless of displacement.

WIDENING OF BRITTLE DEFORMATION ZONES

The relationship between thickness and displacement, in conjunction with strain profiles, may provide the needed criteria to distinguish between individual shear zones of Types 1–3. The positive relationship between thickness and displacement for brittle deformation zones (Fig. 1) suggests strain hardening and widening of BDZ with time (Type 1 behavior). However there are some assumptions to evaluate. We must first assume that time and position are interchangeable variables in natural fault zones, and therefore that different net slips along the zones represent different times in their growth history. In other words, an Eulerian description of the shear-zone geometry, given by the field data, must match the Lagrangian approach of the Means classification (see also Wojtal & Mitra in press). This assumption may be true for Type 1 shear zones propagating and widening at constant rates, but it is difficult to evaluate for natural faults.

We must also assume that the BDZ in Fig. 1 represent a growth sequence. Almost all of the data correspond to different fault zones of various size, not a single zone at different positions: as noted by Blenkinsop & Rutter (1986), individual zones may exhibit D–T relationships that are different to that of the global population. A growth sequence is supported by the model of Scholz (1987), which predicts a positive, linear D–T relationship for BDZ. In addition, the New Jersey BDZ show the same positive correlation for individual faults as they do for the fault population. Positive correlations between T and D are also found experimentally (e.g. Engelder 1974, Teufel 1981).

The margins of BDZ probably strain harden (e.g. by cold working and Hall–Petch hardening) and the zones widen, but the fine-grained portions may eventually soften and accumulate high strains (Mitra 1984, Wojtal & Mitra 1986). The highest D/T ratios are associated with the largest BDZ, but the exponent near unity indicates no systematic increase in strain softening with displacement. The D/T ratios also provide information on the relative, time-averaged rates of displacement and widening. The high average strains (assuming simple shear) suggest slow thickening of the BDZ relative to their displacement rates. The displacement rate is probably controlled by the flow rate of the cataclasites and the rate of fault propagation at the tip, while the rate of widening is a function of grain-size reduction (the rates of crack nucleation and propagation for the different fracture mechanisms).

In addition to their use in evaluating the growth of deformation zones, the empirical D–T relationships have some utility in field studies, though the large uncertainties prohibit detailed application. The scaling laws presented here also suggest that small deformation zones in hand sample or thin section may be analogous to larger zones. Power law frequency distributions of fault thicknesses (Mitra 1979), lengths (Segall & Pollard 1983b) and displacements (Kakimi & Kodama 1974) are also consistent with geometrical self-similarity, though deformation zones may not be strictly self-similar. Studies of the power spectrum of surface roughness for faults and fractures (Brown & Scholz 1985, Scholz & Aviles 1986) suggest the fractal dimension increases with the size of the fracture. Further morphometric and structural analysis of single faults and fault populations is required.

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