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Thickness – displacement relationships for deformation zones: Discussion

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THIS discussion responds to Hull's (1988) article presenting plots of displacement (D) and thickness (T) for cataclastic ('brittle'), mylonitic and 'high strain' deformation zones. The data were bound by lines showing constant displacement–thickness ratios, that varied from 10 to 1000 in the case of cataclastic fault zones, and from 0.1 to 10 for mylonitic fault zones (his figs. 1 and 2). Regression parameters were presented in support of an approximately linear D–T relationship. Hull argued that this relationship was due to a growth sequence, and therefore that cataclastic deformation zones strain harden and widen with time. This discussion points out that there are several fundamental difficulties with this form of data collection, presentation and interpretation in addition to those mentioned in the article. A natural example of a cataclastic fault zone is used to demonstrate that real thickness–displacement relationships are not easily modelled by any of the simple alternatives considered by Hull.

Problems of data collection

Collection of data for displacement is complicated by the fact that displacement is variable along the length of a deformation zone. To deduce a correct evolutionary model, it is essential that both displacement and width are measured at the same point, and that maximum or average values are not used. Hull notes the difficulty of measuring large fault widths. In many mylonite zones, measurable foliation for determining T and γ does not develop *ab initio* until significant shear strain has occurred. This can account for the common observation that new foliation makes an angle of 30° with the shear zone, rather than the predicted 45°, and leads to an underestimate of the width of the zone. It would be useful to distinguish type of fault (thrust, normal or reverse) to remove this as another possible variable in Hull's fig. 1, since different magnitudes of differential stress are anticipated for movement on each type (Sibson 1974).

Problems of data presentation

Data presentation in the form of a log–log plot over eight orders of magnitude potentially conceals important D–T relationships for individual data sets. For example, a set of faults with similar displacements, but no correlation at all between D and T over two orders of magnitude, can be accommodated within the bounding limits of Hull's fig. 1. In the case of Sibson's data for the pseudotachylite-bearing faults of the Outer Hebrides, or Hull's data from Wyoming, the lack of a linear D–T correlation for individual data sets is clear even on his log–log plot of fig. 3.

Problems of interpretation

The major difficulty in interpretation of such data is the assumption that a completely heterogeneous collection of measurements represents a growth sequence. Hull argues from laboratory experiments that this is likely, and indeed it would be apposite to quote in addition Rutter's (1979) experiments on kaolinite rheology and other experiments on clays (Summers & Byerlee 1977, Logan *et al.* 1981, Rutter *et al.* 1986) which suggest strain hardening. However all these experiments are on a very small scale which plots in only the lower-left eighth of Hull's diagrams. Hadizadeh & Rutter (1982) have indicated that there may be major problems in extrapolating the results of laboratory cataclastic deformation to nature at a larger scale, and this is inherent in the physical limitations of the laboratory. Therefore it is probably inappropriate to use such a varied data set to deduce evolutionary sequences for cataclastic deformation zones. Only data from individual faults, or fault sets that can be reasonably inferred to have a common evolution, should be shown on D–T plots for this purpose.

Variation in gouge thickness: a natural example

Figure 1 shows a plot of fault thickness along the length of the fault in the slip direction for a strike-slip fault exposed in the West Asturian–Leonese zone of the Hercynian orogen in North Spain (Blenkinsop 1987). The displacement of the fault can be estimated as 23 m (from bedding and the orientation of the lineation on the fault surface) and is approximately constant over the measured length. In spite of the constant displacement, Fig. 1 shows that the thickness varies by an order of magnitude. The reason for this is seen in Fig. 2, which is a map of part of the fault zone. The fault zone is divided into a number of pea-pod shapes, containing a gouge

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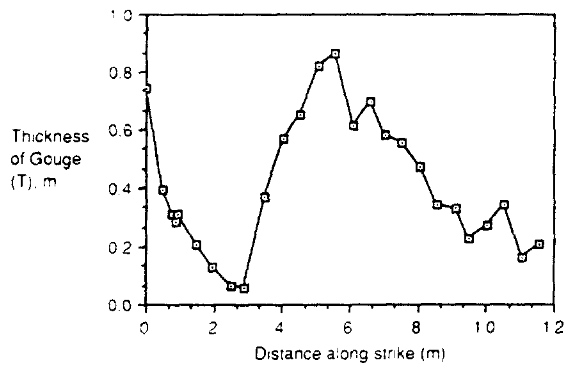

Fig. 1. The relationship between gouge thickness (T) in the direction normal to displacement and distance along the fault in the displacement direction. The fault has a constant displacement of 23 m throughout this section. The periodic fluctuation of an order of magnitude in thickness is due to the pea-pod geometry of the gouge zone.

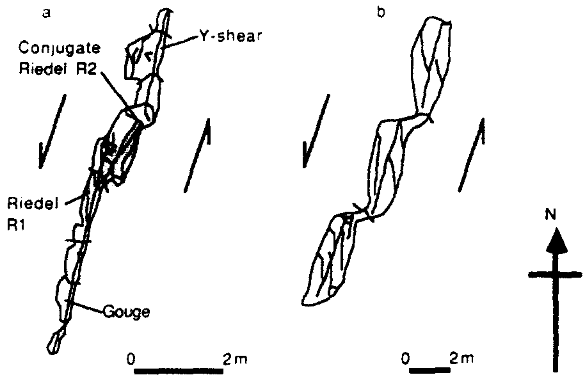

Fig. 2. (a) Detailed map of a gouge pod. Pods are elongate parallel to Riedel R_1 shears, and offset at conjugate Riedel R_2 shears. (b) Schematic en échelon geometry of three gouge pods.

consisting of a white–yellow powder, with red staining by iron oxides and a light blue–grey clay. The whole assemblage consists of quartz, illite, kaolinite and chlorite. Isolated equidimensional fragments of quartzite up to 10 mm across float in this matrix. A P-foliation, Riedel (R_1), conjugate Riedel (R_2) shears, and Y-shears can be identified in the gouge, all giving a consistent sinistral shear sense. This fault is but one of a set of 10 parallel faults with an approximately even spacing of a few metres in the direction perpendicular to the fault planes. The intervening areas are heavily fractured by short (50 mm) shear and mode I fractures that subdivide the quartzite into lozenge-shaped blocks (a protobreccia *sensu*, Blenkinsop & Rutter 1986).

The close comparison between the gouge zone features reported here and experimental features (Rutter *et al.* 1986) suggests that they may share a common stress–strain relationship. Strain hardening may have occurred while deformation spread throughout the gouge by the formation of P-foliation and combined operation of R_1 and R_2 shears. Localization on to the Y-shears may have accompanied a stress drop and a switch to stick–slip oscillation as in the experiments of Logan *et al.* (1981). However a further stage of evolution is evident from the pea-pod shapes of the gouge. Their overall shape is similar to 'ductile stringers' described by Logan *et al.* (1981) or 'trails' by Rutter *et al.* (1986), but the gouge pods are elongate in the direction of R_1 and displaced along R_2, compared to the elongation of stringers or trails in the P-foliation direction and their offset along R_1 in the experiments. Pods are thought to evolve by the operation of R_1 and R_2 shears, like stringers or trails.

A very significant aspect of pod formation is that all shears, even the latest formed Y-shears, are capable of accumulating only limited strain due to their segmented geometry. There must therefore be an overall work hardening and this may explain the spread of deformation to the adjacent set of faults.

However, the resulting D–T relationships on these faults can not be compared to the simple Type 1 shear zone that widens with time (Means 1984, Hull 1988). The en échelon pods show that for the same displacement, order of magnitude differences can be measured in thickness, and that thickness will give a different relationship to displacement at any point along a fault. Different parts of the fault may widen or maintain constant thickness with displacement according to the local relative proportions of strain hardening and softening. Another reason for finding variable thicknesses of gouge along faults is suggested by the field evidence that many natural faults and shear zones evolve by linkage of pre-existing fractures (Segall & Simpson 1986, Blenkinsop & Drury 1988b), a process well known and understood from experiments and modelling (e.g. Cox and Scholz 1988). In these cases, a gouge zone may be produced in the process zone ahead of a propagating crack tip within the intact rock (Vita-Finzi & King 1985, Hancock & Barka 1987, Blenkinsop & Drury 1988a). This volume might be expected to have thicker gouge than parts of the fault adjacent to the pre-existing fractures.

Conclusion

The analysis presented by Hull is questioned because of problems in data collection, presentation and the interpretation of D–T relationships as a growth sequence. These relationships should *not* be used to predict displacements from gouge thickness, even for 'brittle deformation zones', until such a sequence has been established. Gouge zone thickness probably evolves in a more complex manner depending on the operation of Riedel, conjugate Riedel and Y-shears.

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Thickness–displacement relationships for deformation zones: Reply

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IN MY original Short Note (Hull 1988), I presented some empirical relationships between thickness (T) and displacement (D) for different types of natural deformation zones in quartzofeldspathic rocks. In the continuing effort for brevity, I will not quote large passages from that Short Note in reply to Dr Blenkinsop's Discussion. The interested reader is therefore urged to read the original note carefully.

Many of Blenkinsop's comments are simply in error. He incorrectly refers to the lines of unit slope in figs. 1 and 2 (Hull 1988) as "bounding limits". These lines illustrate constant D/T ratios *for reference only* and were never referred to as "bounding limits" or "bounds to the data". Blenkinsop is critical of my alleged use of laboratory data, but experimentally determined D–T values were *explicitly* omitted from the compilations. I stated in the original note that the data corresponded to "natural BDZ only" (Hull 1988). The 'displacements' on pseudotachylite-bearing faults from Scotland (Sibson 1975) are actually separations, as originally discussed by Sibson (1975) and repeated in my article. Blenkinsop is also wrong when he states that the pseudotachylite data are "uncorrelated". Sibson (1975) presented a linear relationship between log T and log 'D' for the pseudotachylites, and used this positive correlation to discuss heat-generating capacity and resistance to slip. Blenkinsop incorrectly refers to the data presented in figs. 1 and 2 (Hull 1988) as "completely heterogeneous"; in fact, these plots are dominated by a few individual populations of deformation zones, as will be discussed later.

Many of Blenkinsop's comments seem redundant. He criticizes the temporal growth models of Means (1984) as too "simple", but these models represent end-member behavior of idealized simple shear zones, not natural faults. Fault zones are naturally more complex. For example, "the margins of brittle deformation zones probably strain harden and the zones widen, but the fine-grained portions may eventually soften and accumulate high strains" (Hull 1988). Compare this statement with one of Blenkinsop's principal conclusions: "Different parts of the fault may widen or maintain constant thickness with displacement according to the local relative proportions of strain hardening or softening". The state of stress as a variable controlling T–D relationships, also mentioned by Blenkinsop, was carefully discussed in the original article (see also Robertson 1983, Scholz 1987). Blenkinsop briefly notes other concerns about measuring T and D, the use of average values, the assumption of a growth sequence,

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