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SHORT NOTES

Thickness–displacement relationships for fault zones

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Abstract—Fault zone thickness and displacement data have been used in recent studies to infer a global linear relationship between the two parameters in log–log space, and based on this empirical relationship, several models of fault growth have been proposed. Examination of the original data sets, but on linear graphs, indicates that there is a wide statistical variability of many of the data, and that larger values of displacement along faults are only generally related to an increase of fault zone thickness. The earlier data do not confirm a thickness–displacement relationship for faults of similar displacement, nor for faults in similar rock types. Reasons for the lack of correlation may be the wide range of rock types, structural settings, and processes responsible for the development of the faults measured. An example of thickness variations along the Bismark fault, southwest Montana, shows the variations of fault zone thickness along strike and down plunge. Conceptual and quantitative models which rely heavily on thickness–displacement relationships should be considered with caution until further data are collected on the topic. Future studies should explicitly state the criteria used to determine faulted and unfaulted rock, present in explicit form the slip vector used to determine net offset, and present, if possible, measurements of thickness and displacement from: (1) different points along the same fault, (2) families of faults in similar rock types with different amounts of slip, and (3) faults with similar amounts of net slip in similar structural settings.

RECENT interest in the dimensions of faults and, in particular, discussions of fault zone thickness and displacement (Robertson 1983, 1988, Hull 1988, 1989, Blenkinsop 1989) and their application to fault zone growth models (Scholz 1987, Hull 1988) point to a renewed interest in applying observations of the size of a fault to a genetic model of fault growth. The purpose of this note is to discuss the interpretations of data on fault zone thicknesses and displacements and the implications of these data for models of fault zone evolution. I briefly discuss the original data sets, the statistical treatment of these data, and the use of these data with regard to conceptual and mechanical models of fault zone growth. Finally, I propose several criteria for the collection of data which bear on the problems of fault dimensions and fault growth.

Hull (1988) is the most recent of a growing body of work on fault zone thickness and displacement data for cataclasites, mylonites and pseudotachylites. The data on the fault zones were first presented in Otsuki (1978), Robertson (1983) and Hull *et al.* (1986), with several other data from Segall & Pollard (1983), Segall & Simpson (1986), and one data pair from each of Mitra (1984) and Fletcher & Gay (1971). The data discussed here are shown in Fig. 1. I have used the data from sources which present the thickness and displacement data in an explicit form, so do not include data from Segall & Pollard (1983), Mitra (1984), Chester & Logan (1986) or Segall & Simpson (1986). I have also excluded data from experimental work presented by Robertson (1983) but used all of his natural fault data. No data from mylonites are considered in this note. This gives 73 sets of data pairs, as compared to 75 data pairs shown on fig. 1 of both Hull (1988) and Scholz (1987). I have included all of the data summarized in Otsuki (1978). The thickness–displacement (T–D) data have been previously presented in logarithmic plots (Fig. 1) to facilitate the presentation of the data in a compact figure (Otsuki 1978, Robertson 1983, Scholz 1987, Hull 1988, Robertson 1988). Data on the logarithmic plots are then used to generate a best-fit line usually of the form (see Fig. 1):

$$Y = aX^b,$$

where: $Y = \log[\text{displacement}]$, $X = \log[\text{thickness}]$, a and b are coefficients of the best-fit line to the data.

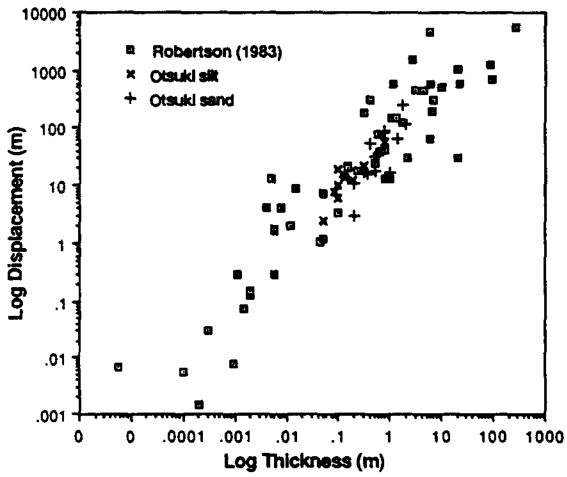


Fig. 1. Graph of the log displacement vs log fault thickness for 73 faults. Data from Otsuki (1978) and Robertson (1983).

The linear relationship on the logarithmic plots commonly derived from the data has been used to suggest that there is a linear correlation between the thickness and displacement of fault zones (Scholz 1987, Hull 1988). A general, linear trend exists only in the logarithmic plots; the data do not exhibit any simple correlation in linear scatter plots (Figs. 2–4). The logarithmic graphs of the data compress data to a linearized cluster which appears to have a relatively good correlation—a point debated elsewhere (Blenkinsop 1989, Hull 1989). The artificial clustering of the data is displayed in the large displacement data (Figs. 3a & b) where the largest data are compressed on the log–log plot. The spread of the data, which is readily apparent in the linear plot, ranges over as much as two orders of magnitude of displacement for a given value of thickness, and over two orders of magnitude of the thickness for a given value of displacement. Whereas many workers (e.g. Watterson 1986, Scholz 1987, Hull 1988, 1989) are clearly aware of the implications of log–log plots, it is still useful to note for those who may be unfamiliar with the data sets that the compressed data may yield an artificial confidence not warranted by the original data sets.

The data from which these relationships were derived were collected by many workers, and the measurements were made on faults from a wide range of rock types, including sandstones, quartzites, quartz monzonites, gneisses and shales. In addition, data are from several different types of faults, and occur in various geologic settings. I have broken the data out with respect to both lithology and amount of displacement (Figs. 2–4) to determine if sub-populations of the data exhibit any correlation, and also as a test for the robustness of the data sets (Mann 1987). The same relationship holds for all of the smaller populations, either broken out by lithology or by amount of displacement; there is no *T–D*

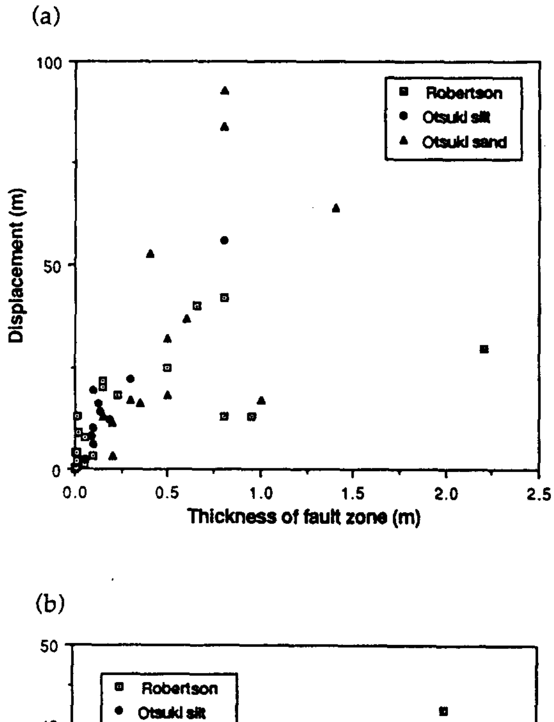


Fig. 2. (a) Linear plot of fault displacement and thickness data from Fig. 1 for faults with displacement of 100 m or less. A linear regression of the data gives an equation of $Y = -8.87 + (87.37X)$, and a correlation coefficient $R^2 = 0.629$. (b) Linear plot of fault displacement and thickness data from Fig. 1 for faults with displacement of 50 m or less. (a) & (b) show that the scatter of the data is pronounced at all scales of observation in a linear plot.

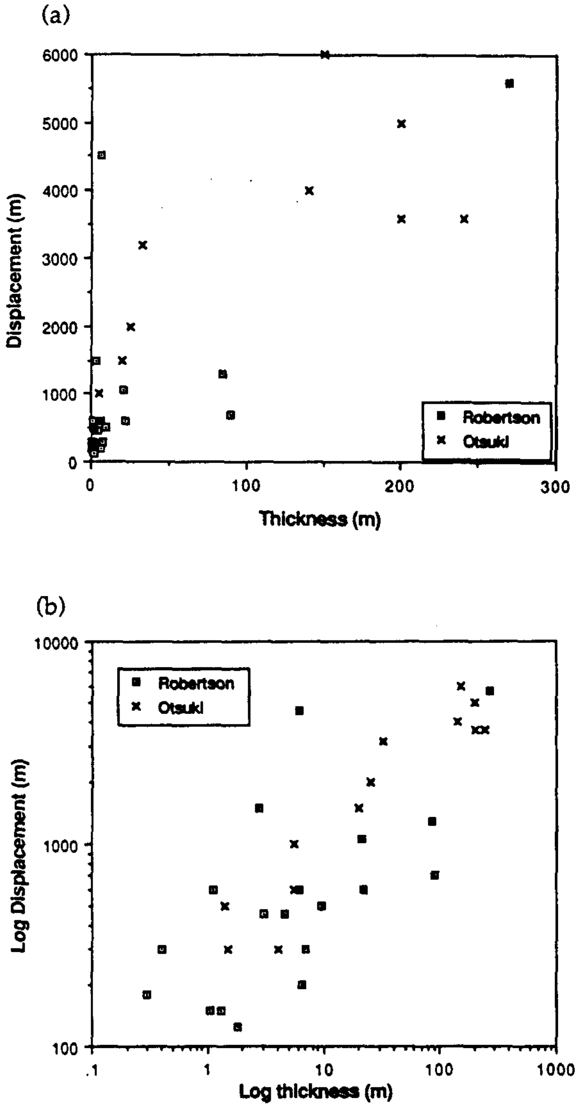


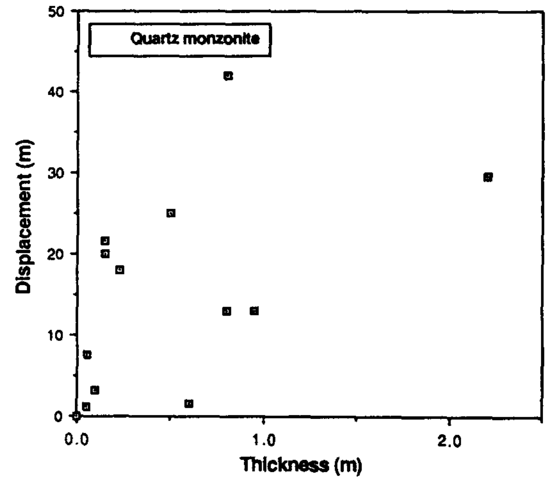
Fig. 3. (a) Linear plot of fault displacement and thickness data from faults with displacements in excess of 300 m. Data are from Otsuki (1978, and references therein) and Robertson (1983). Note the large scatter of the data for the faults with displacements greater than 1 km. (b) Log–log plot of fault displacement and thickness data from faults with displacements in excess of 300 m. Some compression of data towards an apparent linear trend occurs, but the data contain two orders of magnitude variation. Variability may be due to the influence of other factors on fault zone thickness.

correlation in the linear data sets, and in some of the smaller populations based on both lithology and displacement, there is a poor correlation even in the log–log plots (Fig. 4b). Some of the smaller populations can be fitted with a polynomial, logarithmic or exponential fit which is as good, or better, than the linear regression. This indicates that: (1) there may be no linear relationship between the two variables on the basis of either displacement along the fault or lithology, and/or (2) the data sets are too small to be statistically significant. Contrary to Robertson (1988), there seems to be no causal relationship between thickness and displacement of a fault for a given lithology.

Several authors have found no correlation between fault zone thickness and the displacement along the fault (Jamison & Stearns 1982, Blenkinsop & Rutter 1986, Woodward *et al.* 1988). Furthermore, fault zone thickness may vary greatly along the fault trace or in the dip direction with little or no change in displacement (see, for example, Hobbs *et al.* 1965, Knill 1972, Morris & Lovering 1979, Wallace & Morris 1986, Woodward *et al.* 1988). Robertson (1983, 1988) does not account for the variation of thickness along the fault zones, and it is unclear if other workers cited above have examined this variation. Data on fault zone thickness presented by Otsuki (1978), Robertson (1983, 1988) and Hull (1988) do not discuss how thicknesses were measured relative to the slip vector of the fault and what criteria were used to distinguish faulted from unfaulted rock. Some of the work cited in recent discussions of fault morphology (Chester & Logan 1986, Segall & Simpson 1986) do not explicitly state the dimensions of the faults, and use of qualitative descriptions of *T–D* relationships is not rigorous support for the model. The data presented in Figs. 1–4 do not include other data for which there is no general relationship between thickness and displacement, and do not account for variations of fault zone morphology along strike or down-dip. Thus, as pointed out by Blenkinsop & Rutter (1986) and Blenkinsop (1989), it is not possible to determine if the *T–D* relationship for a single fault will be reflected in the entire data set. The linear and logarithmic plots of these data indicate a *general* increase in displacement with thickness, but the scatter of data show that this is a qualitative relationship which requires much more work before a causal relationship is determined. It seems more appropriate to determine the *T–D* relationship for individual faults or related sets of faults (Hull 1989) and use these data as a guide for developing models of fault growth. The inferred "simple proportionality" (Scholz 1987) between *T* and *D* seems to be an artifact of the logarithmic plots and regression in log–log space, and does not as yet reflect a causal relationship for the global population of faults. The wide scatter of most fault zone thickness and displacement data may be a result of other variables affecting the fault zone thickness not included in the *T–D* plot, such as lithology of protolith, rheology of the fault zone material and the structural setting of the fault.

An example of the variation of the thickness of a fault along strike and with structural level is shown in Fig. 5. The Bismark fault in southwestern Montana is a reverse fault with a significant amount of left-lateral slip (Schmidt & Garihan 1983). The fault juxtaposes a variety of rock types along its trace, and cores a NW-plunging anticline. Down-plunge projections of the structures indicate that the fault may represent as much as 6.5 km of structural relief (Evans & Schmidt 1988). In the structurally highest part of the fault, Archean quartzo-feldspathic gneisses are juxtaposed against Paleozoic sedimentary rocks and the entire fault zone is approximately 30 m thick. Slip is concentrated on narrow faults which nucleated in extension and shear fractures in plagioclase grains. The middle suite of samples comes from a section of the fault in which Cretaceous granite is faulted next to Archean gneisses and may be as much as 4 km deeper than the highest section. Within the granite, the fault zone consists of a

(a)



(b)

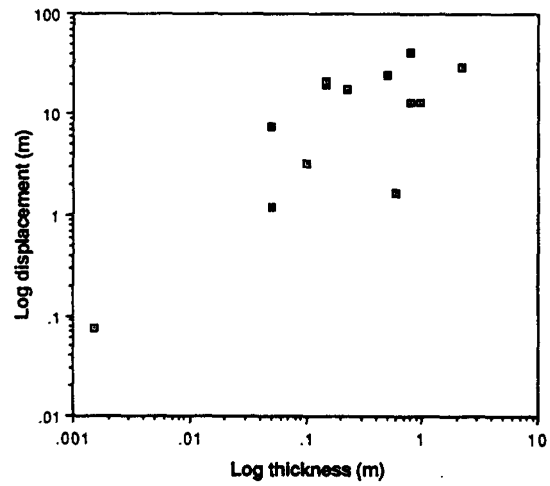


Fig. 4. (a) Linear plot of fault displacement and thickness data from faults with displacements of 50 m or less in quartz monzonite rock. Data from Robertson (1983). A linear regression gives $D = 9.69 + 10.59T$, and a correlation coefficient $R^2 = 0.26$. (b) Log–log plot of fault displacement and thickness data from faults with displacements of 50 m or less in quartz monzonite rock shown in (a). Data from Robertson (1983). Equation of the regression and correlation coefficient are $D = 24.30\,(T^{0.75})$, $R^2 = 0.64$.

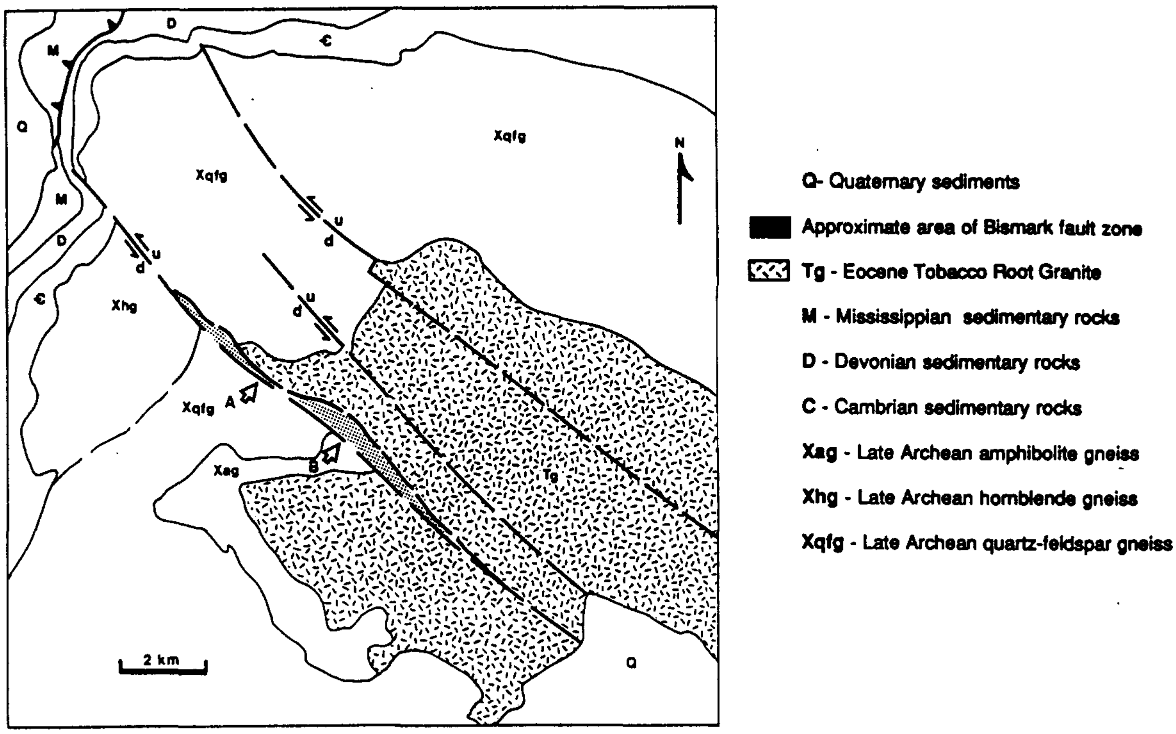


Fig. 5. Simplified geologic map of the Bismark fault, central Tobacco Root Range, southwestern Montana, based on Vitaliano & Cordua (1979) and unpublished mapping by J. P. Evans. Northwest-striking reverse oblique slip faults cut the Tobacco Root Granite (Tg), Archean gneisses and Paleozoic rocks. Fault zone of the Bismark fault (stippled pattern) varies in width from 50 m at point A to over 450 m at point B, a distance approximately 2 km along strike. Net slip on the fault is approximately the same in both locations. Mean slip vector is oriented 24°/121°, with approximately 3.5 km of left strike separation and 2.0–5.0 km of reverse slip (Schmidt & Garihan 1983).

~6 m thick zone of intense deformation which has a sharp boundary with a 15 m thick zone of faulted and fractured granite. At the deepest part of the fault the Bismark fault places Cretaceous granite on Archean amphibolite gneiss, and most of the deformation is in a fault zone over 400 m thick in the hanging-wall granite. Deformation in the hornblende gneisses of the footwall is confined to very narrow (~10 mm) shear zones that contain biotite, calcite and chlorite distributed over a 20 m thick region. In this example, the thickness of the fault varies over two orders of magnitude along the 5 km long region for which slip is relatively constant, and from this example, no simple *T–D* relationship is apparent.

Scholz (1987) presents a mechanical wear model motivated by the linear relationship exhibited in the logarithmic plots, and Hull (1988) discusses the growth of fault zones and the processes of strain softening and strain hardening during fault zone evolution in light of these data based on a conceptual model of fault growth developed by Means (1984). Because of the uncertainties of the *T–D* data themselves, the problems involved in statistical treatment of data collected by numerous workers using different and commonly unreported criteria, reported in a wide range of styles, and lack of data which indicate a negative result (see Wachter 1988), it appears unwarranted *at present* to use these data as motivations for quantitative models of fault and shear zone growth. Means (1984) and Hull (1988, 1989) have presented useful models of fault development which will no doubt guide many workers in the future, but the processes by which faults nucleate and grow do not always yield simple morphological relationships. Faults may evolve from a strain-hardening to strain-softening zone over time (Wojtal & Mitra 1988), localizing slip along narrow regions of cataclasis (e.g. Evans 1988), or widening may be prevented by the rheology of rocks in the hanging wall or footwall (Erickson & Wiltschko 1989). A thickness–displacement relationship for such a fault would underestimate the amount if slip on the entire zone, as much of the deformation may take place in a fraction of the entire fault zone.

The *T–D* data to date come from too broad a variety of lithologies and structural settings to engender confidence, and it is not yet clear what processes are active as faults evolve by either thickening, as suggested by Hull (1988), or by strain localization (Wojtal & Mitra 1988). The data of Robertson (1983) still comprise the majority of the reported *T–D* data obtained to date, and Robertson (1983) initially pointed out that his data support only a qualitative measure of the correlation between thickness and displacement. Logarithmic plots of fault zone thickness and displacement are useful in presenting data in a compact form, but examination of the data does not support any simple relationship between mechanisms and morphology. Hull (1988, 1989) rightly suggests that more data on the morphology of fault zones must be collected to answer the questions regarding the physics of fault growth. Future studies in this topic should focus on: (1) single faults along which at least several measurements of net slip, slip vectors and thickness can be made, such as in underground excavations, tunnels and mines, or in well-exposed field examples; (2) faults in similar rock types with different amounts of slip; and (3) faults with similar amounts of slip. In addition, it would be beneficial to all workers if the criteria for defining faulted and unfaulted rock are stated, along with an explicit description of the slip vectors used in determining offset. Thickness–displacement relationships may exist for some populations, but may vary between populations depending on fault type, rock rheology and environmental parameters; in other cases some faults may not conform to a global population.

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