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Reply to comment on "Fault zone strength and failure criteria"

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I thank *Lockner et al.* [*this issue*], hereafter referred to as *LBS*, for their interest in this work. *LBS* suggest that I [*Marone*, 1995] misunderstood their analysis and that their proposed empirical relation is indeed valid. I do not agree. I do not deny that *LBS* have established some form of empirical relationship, only the specific form of the relation and its theoretical basis are at issue.

There are two basic problems with the *LBS* analysis: 1) they suggest that an empirical relation has been established between the coefficient of internal friction of intact rock μ_i and the coefficient of friction of fault gouge μ_a, yet their analysis does not involve μ_i, but rather another parameter, and 2) the transformation rule used to derive their empirical relation is not valid for the parameters and data sets they use. Because of their potential significance for the failure criteria of tectonic faults it is important to evaluate carefully the issues under discussion.

Background, Significance, and Issues

I studied shear of simulated fault gouge between rough surfaces (mated tension fractures) and found that a critical gouge layer thickness is required to effect the transition from standard Coulomb failure to failure governed by a modified criterion appropriate for simple shear of a bounded gouge layer [*Marone*, 1995]. For the modified criterion, referred to as Coulomb plasticity, the maximum principal stress is oriented 45° to the gouge layer, irrespective of the external stress state [*Hobbs et al.*, 1990; *Marone et al.*, 1992; *Byerlee and Savage*, 1992]. My work was motivated by the question of whether the stress state for Coulomb plasticity requires a gouge layer of finite thickness, or if the transition from Coulomb failure to Coulomb plasticity occurs immediately upon fracture of an intact rock (as implied implicitly by *LBS's* analysis and proposed empirical relation). In addressing this issue, I pointed out [*Marone*, 1995] that differences between the fracture strength of intact rock and the frictional strength of rock surfaces cannot be explained solely by differences in the corresponding stress states and boundary conditions, but that differences in the Coulomb parameters of cohesion C and friction angle ϕ must also be accounted for, in contrast to previous suggestions [*Lockner et al.*, 1992; *Lockner and Byerlee*, 1993].

Three points are at issue between *LBS* and myself: 1) whether an empirical link has been established between the true coefficient of internal friction of a material μ_i and the apparent coefficient of friction of a gouge layer of that material deforming in simple shear μ_a, 2) the validity of the theoretical basis for their empirical relation, and 3) implications of the empirical relation for the stress state and failure criteria for brittle failure of faults.

LBS use a transformation rule originally discussed in the context of simple shear of a gouge layer by *Hobbs et al.* [1990]

$$\mu_a = \tan\phi_a = \sin\phi = \sin(\tan^{-1}\mu_i), \qquad (1)$$

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where ϕ_a is the apparent friction angle. This relation specifies that the apparent coefficient of sliding friction of a layer of fault gouge deformed in simple shear is less than the true coefficient of sliding friction [*Marone*, 1995]. Similar statements can be made about the friction angles or coefficients internal friction and thus (1) has important implications for rate/state dependent friction [*Marone et al.*, 1992; *Beeler and Tullis*, 1995] and fault strength [*Hobbs et al.*, 1990; *Byerlee and Savage*, 1992; *Scott et al.*, 1994].

LBS apply (1) to estimates of μ_i for intact rock and report agreement between the resulting μ_a values and laboratory measurements of gouge friction. Their empirical relationship, however, does not involve the coefficient of internal friction, contrary to the statement made in the first sentence of their comment. They present a valid definition of μ_i (their equation 2), however, they use another parameter: the ratio of fracture strength to normal stress (see discussion following their equation 4), which hereafter I refer to as μ^*. Although *LBS* see this as a minor issue, there are two important reasons why it is not. First, equation (1) involves the true coefficient of internal friction, and not the hybrid parameter μ^*, and second, (1) is only valid under certain conditions, which are not met for the data considered by *LBS*.

Proposed Empirical Relationship

In Figure 1, I show the data and analysis used by *Lockner and Byerlee* [1993] and *Marone* [1995]. To simplify comparison I use the notation of *LBS* with two exceptions. 1) I use μ_i as the true coefficient of internal friction and refer to their parameter as μ^*. 2) Following Lockner and Byerlee [1993] and Marone [1995], I use σ_c as the normal stress intercept of the true and apparent failure envelopes (Figure 1), whereas in their comment *LBS* refer to this as σ_c'. Figure 1a shows fracture data [*Byerlee*, 1966] for Westerly granite. The data are fit with a Coulomb failure law $\mu_i = \tau_p/(\sigma_p+\sigma_c)$, where τ_p and σ_p are the shear and normal stress at the point of fracture.

For a given data set, the Coulomb parameters are normally defined by fitting data to the Coulomb law (Figure 1a). However, *LBS* use a different approach. They calculate another parameter (my μ^*, their μ_i) by applying the Coulomb relation to individual fracture datum for fixed values of σ_c. In an initial publication they took σ_c=0 [*Lockner et al.*, 1992] and later they used σ_c=20MPa [*Lockner and Byerlee*, 1993]. However, the values so determined do not involve the local slope of the data and thus, by definition, are not μ_i (Figure 1a).

Figure 1b shows μ_i values obtained for three values of σ_c. For low values of σ_c, μ_i decreases strongly with normal stress, due to the diminishing effect of cohesion at higher normal stress. If the transformation rule (1) is applied to these μ_i values, the resulting μ_a values agree roughly with Byerlee's law, which is the basis of *LBS*'s empirical relationship. Thus, in this sense, I agree that *LBS* have established an empirical relationship. However, this is a not a relationship between μ_i and μ_a, but rather between μ^* and μ_a.

Although attention has focused primarily on linear failure laws, the same issues exist for non-linear failure laws, due to the parameter σ_c. The transformation rule (1) requires that σ_c be the

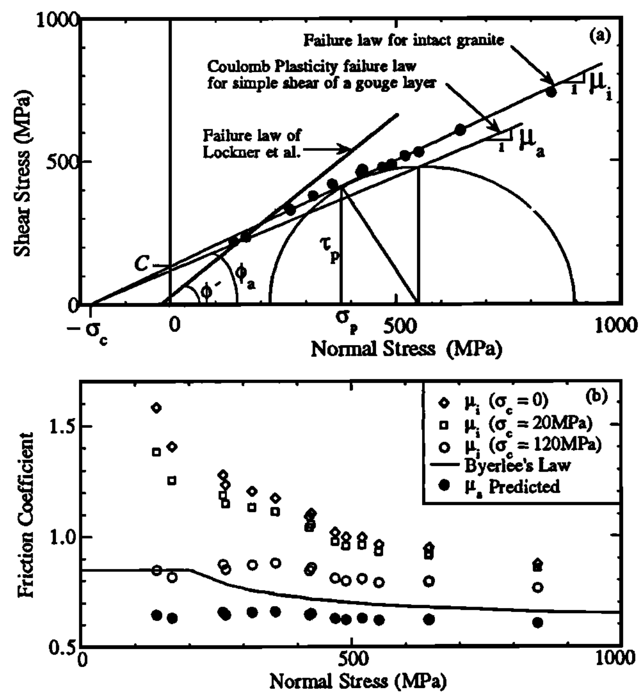

Figure 1. Relationship between failure criteria, fracture data, and internal friction. (a) Dots are fracture data for Westerly granite [*Byerlee*, 1966]. Line of slope μ_i is the Coulomb failure envelope determined by a least squares fit to the data: σ_c = 187.6MPa and μ_i =0.73 (R=0.995). Line of slope μ_a is the Coulomb plasticity failure criterion and yields apparent friction angle ϕ_a. Line of angle ϕ' indicates one of the failure laws used by *LBS* who arbitrarily assume a value for σ_c and fit a failure law to each fracture datum individually. (b) Coefficient of internal friction derived from the fracture data for three σ_c values. *Byerlee* [1966] reported cohesion of 70 -170 MPa for these data, which would require σ_c of at least 120MPa. This yields predicted μ_a values that are significantly below laboratory measurements of gouge strength, which scatter about Byerlee's law. (Modified from *Marone*, 1995.)

same for both data sets used to derive μ_i and μ_a (see the geometry of Figure 1a). For fault gouge, σ_c is $\approx$ 0, whereas, σ_c is not zero for intact rock. For the data of Figure 1a, σ_c is 187.6 MPa. Thus, a specific flaw in the analysis of *LBS* is that of assuming that σ_c can be treated as a free parameter that can be arbitrarily set to zero. When the correct σ_c value is used, the basis for the proposed relation fails (Figure 1b).

Another aspect of *LBS's* expanded analysis requires comment. They suggest that fracture data can be related to friction of gouge $\mu_a = \tau_s / \sigma_p$ via: $\tau_s / \sigma_p = \tau_p /(\tau_p^2 + \sigma_p^2)^{1/2}$, where τ_s is the shear stress required for sliding of gouge (their equation 1). *LBS* note that this relation is also obtained by substitution of the Coulomb law into (1) if σ_c=0. As justification for taking σ_c=0, *LBS* make a series of assumptions about their parameters ϕ', ϕ'', and σ_c'' (see their Figure 1). In particular, they take σ_c''=0, which implies $\phi' = \phi''$. They note that for the available data ϕ' is slightly larger than ϕ'' and thus, with respect to their proposed empirical relation, they state that "the agreement would be improved if the vertex from which ϕ' was measured were moved to the left."

It is important to note the distinction between ϕ, ϕ', and ϕ'' in their Figure 1, since the casual reader may assume that ϕ' is a friction angle (ϕ = $\tan^{-1}\mu_i$), in which case the shear strength of gouge would be greater than the fracture strength of a like material: $\tau_s \geq \tau_p$ if σ_c''=0 and $\phi' = \phi''$. Similarly, although *LBS* show σ_c' in association with ϕ, the values they use (0 and 20MPa) are more appropriately linked to ϕ'. Then their "shift in vertex from which ϕ' is measured" results in a simple, linear Coulomb failure criteria, and the associated reduction in ϕ' is just that due to having larger σ_c. Moreover, although *LBS* refer to non-linear failure criteria, their assumptions regarding ϕ', ϕ'', σ_c' and σ_c'' have the same outcome: the transformation rule (1) requires that $\sigma_c' = \sigma_c''$, even if σ_c depends on normal stress as in a non-linear failure law.

Implications for the Strength of Mature Faults

Although *LBS* indeed have established an empirical link between fracture strength and friction of gouge, in my view it is not a legitimate relationship between the true and apparent coefficient of internal friction. Furthermore, the proposed theoretical basis for it does not apply because they treat parameters of the failure criteria as if they were free parameters. The transformation rule (1) requires that σ_c be the same for both intact rock and a gouge layer, and thus application of (1) or *LBS's* equation (1) requires *a priori* determination of σ_c from the data.

The proposed empirical relationship is potentially very interesting, since it implies that differences in μ_i for intact rock and μ_a for a gouge layer are related solely to differences in the stress state and boundary conditions for failure, and hence that the true failure parameters are the same in both cases. Further, the result implies that the stress state for Coulomb plasticity develops immediately upon the formation of a fracture and does not require a gouge zone of finite thickness. However, laboratory data indicate that a gouge zone of finite thickness is necessary for the development of Coulomb plasticity and thus shear on incipient fractures obeys the standard Coulomb criterion [*Marone*, 1995]. Applied to natural faults, this implies that faults should weaken with accumulated slip, as wear occurs and the gouge zone widens [*Marone*, 1995]. However the magnitude of this weakening effect is small (for example, the coefficient of sliding friction would change from 0.75 to 0.6) and thus it is not a significant contribution to the apparent weakness of mature faults, contrary to the assertions of *Lockner and Byerlee* [1993].

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