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Discussion

Reply to the comment by K. Mulchrone on: "Flattening in shear zones under constant volume: a theoretical evaluation" by N. Mandal, C. Chakraborty and S, Samanta☆

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1. Introduction

In the kinematic analysis of transpression zones, several previous workers (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Robin and Cruden, 1994; Dutton, 1997; Jones et al., 1997) have applied continuum models. We presented a similar model to estimate the amounts of flattening in ductile shear zones that are physically possible in natural conditions. The model considers a viscous layer, simulating the shear zone, sandwiched between two rigid or deformable blocks. The movement on the blocks induces flow in the viscous layer. In our analysis we made a balance of energies associated with the movement of the blocks with that of the flow in the viscous layer, and calculated the ratio of bulk movements across and along the shear zone.

Mulchrone (2003) has misconstrued our model, which probably led him to discover incorrectness in the analysis. The misconception appears to have crept in from figure 1 of Mandal et al. (2001) where the boundary walls of the shear zone are shown as thick lines. We reiterate that the shear zone of our model is to be considered as bounded by rigid/deformable plates simulating less deformed rocks that confine natural high strain zones (cf. Ramsay and Huber, 1987). In our paper we have analyzed the kinematics of the bounding plates independent of the material flow within the shear zone. The entity of the plates should not be confused with that of the material plane within the shear zone rocks representing the interface with the bounding plates. We apprehend that Mulchrone has reviewed our analysis with the wrong notion that the boundary walls represent the interface of the shear zone rocks, which we never meant and believe would hardly ever mean to geologists familiar with natural shear zones! We indeed considered kinematics of the shear zone interface, but independent of the motion of the bounding plates as outlined below.

2. Mathematical considerations

Mulchrone (2003) has provided long mathematical derivations to estimate the energy involved in the flow of the shear zone rocks, compared the result with our Eq. 2 and found them to be identical! This is no wonder, because our Eq. 2 also represents the energy involved in the flow of the shear zone rocks, which we derived in the same way as Mulchrone has done. In our paper we compared Eq. 2 with Eq. A8 that represents the work done for movement of the bounding plates in order to recognize the effects of length/thickness ratio on the shear zone flattening. In the following paragraphs we attempt to show that he has looked at the analysis giving no effort to understanding the physical basis of our theoretical model.

Our theoretical model actually relates the strain energy with the mechanical energy associated with body movement of the shear zone walls. According to the classical mechanics, if a body experiences displacement d under a force F, then the work done (i.e. mechanical energy) is $F \times d$. In our case we have taken F as $\sigma_n l$, where σ_n is the global normal stress in the direction of shear zone normal,

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and l is the length of the shear zone. The balance between the energy input to the shear zone and the strain energy involved in the flow of material with the shear zone can be demonstrated in terms of deformation of a physical model under a hydraulic press. The energy supplied to the deforming model is pAd, where d is the relative travel distance of the hydraulic pistons within which the model is squeezed, A is the cross-sectional area of the pistons, and p is the hydraulic pressure that acts normally to the opposite face of the moving piston. This p is considered to be the global normal stress in our case. The work done in the movement of the piston can be balanced with the strain energy associated with the deformation of the model, assuming that there is no energy loss by any other means. This simple principle was applied in developing our theoretical model.

The above discussion also resolves one of his major points, which states incorrectly our consideration of the normal stress. We nowhere mention that the normal stress is considered at the interface of the shear zone walls and the viscous block. It is quite apparent that the stresses develop at the interface due to the flow of the viscous material and the normal stress component to the wall is thus likely to be heterogeneous, as the flow is heterogeneous. However, it is not clearly understood how violation of Newton's third law is in question. This kind of analysis requires imposing the condition of dynamic equilibrium, for which we need to consider all the stress components acting upon the body. In our case, one face of the wall is subjected to a total force of $\sigma_n l$, and the opposite face of the wall experiences traction of the flowing viscous matrix. The basic condition that needs to be satisfied is the equilibrium of all these forces. The analysis could also be developed by balancing these forces acting upon the walls. We have, however, utilized an energy balance merely for obtaining the mathematical derivations in a simple way. In addition, it may be noted that Mulchrone has used the equations of Jaeger (1969) giving the normal stresses along the flattening direction, and determined the work done in the displacement of the boundaries defining the viscous block. In Jaeger's derivations one can find that the pressure at the ends of the plates is made zero to obtain the stress components. This specific assumption need not to be imposed if we develop the relation in terms of balancing energies associated with the displacement of walls and the flow of material with the shear zone.

Mulchrone's (2003) derivation for work-done of the shear zone boundary (Eq. 18) reveals that our expression (Eq. A8) is twice his. This difference is due to a difference in physical considerations. In order to keep conformity with real geological situations, we have considered that the flow in shear zones also involves lateral displacement of wall rocks at both the ends. The overall displacement of the system during flattening is considered to follow that of pure shear. In order to clarify this, we take an example of shear zones with deformable walls. Considering $\eta_s = \eta_w$, we can test whether an equality is maintained between Eqs. A2 and A8. In this case the block will undergo homogeneous deformation and in pure shear ϵ_{xy} in Eq. (2) will be zero and $\epsilon_{xx} = -\epsilon_{yy}$. The equation then gives rise to: $E_p = 16lt\epsilon_{xx}^2$. Now, replacing $p\cos 2\alpha = \sigma_n = 2\eta_s\epsilon_{yy}$ and $v_b = \epsilon_{yy}t$, we get an identical expression of E_p in Eq. A8. To maintain a generality in the analysis we had to consider the expression of A8 in this way, which does not disturb the main proposition of our paper.

Mulchrone (2003) has pointed out that there has been confusion in the use of differential versus deviatoric stress. This is not a correct claim. In Eq. (A7) we clearly mention that the bulk normal and shear stress is determined in terms of a parameter p, where $p = (\sigma_1 - \sigma_2)/2$. There has been only a printing mistake while describing p in the text. It would be 'half the differential stress'.

3. Summary

1. Mulchrone's analysis is made on physical considerations different from ours. This difference has led to an erroneous interpretation of our analysis.
2. The solution given by Mulchrone is similar to the energy calculation in the flow of viscous blocks presented in our paper. We actually related this with the energy input to the system associated with the displacement of walls under the bulk normal stress.
3. The question of violation of Newton's third law seems irrelevant. In this kind of analysis the condition of equilibrium of all forces acting upon the body is generally imposed.
4. The expression of p is clearly mentioned in terms of a mathematical equation. So, there cannot be any confusion between differential and deviatoric stress.

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