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Ductile shear zones as counterflow boundaries in pseudoplastic fluids: Reply

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I thank Raymond Fletcher for his elegant demolition of my crude adaptation to counterflow of Turcotte and Schubert's (1982) expression for channel flow. I also thank Sonder for the same (and other) correction(s) incidental to developing her very welcome alternative explanation for the same suite of curves that I found empirically to forward model shear zones and fit several geological examples.

I apologise to everybody for having unintentionally violated Newton's third law and for introducing no-slip boundaries to the outer margins of shear zones. The referees are absolved of responsibility for my mistake because I added the flawed section on dynamics after reading their comments.

Leslie Sonder's contribution allows me to claim that some good came from my flawed attempt to read rock rheology from displacement profiles associated with ductile shear zones. This progress comes not only from her alternative theory but also from the partial convergence between field geologists beginning from frozen kinematics and geophysicists focusing on the dynamics and some key geophysical references. I adopt here the terminology of S or J curves across symmetric and asymmetric shear zones respectively. I stand corrected about J curves along ocean transforms but note that my analysis resulted in the same $n = 3$ for the ductile ocean floor as the literature quoted by Sonder. As pointed out in Talbot (1999) several of the examples there fit the curves used only locally.

Changing rock rheologies across shear zones has long been advocated in general terms so I congratulate Sonder on her beautiful theory based on the simplest drive of all, the relative motions between two sides of a *single* shear zone. I do so on the grounds that it satisfies a simple criterion that can be used to check any new theory of ductile shear, whether or not it make sense of the S or J curves found along natural shear zones. However, I consider that Sonder threw the baby out with the bathwater when she dismissed a pressure-driven drive and replaced the no-slip counterflow boundary by a simple change in sign in velocity. Sonder changed C in her expression 2 whereas the Talbot (1999) aimed to change only n.

The asymmetric shear zones on either side of diapiric contacts illustrate that at least some natural boundary shears can be driven by pressure gradients differing across a shared no-slip boundary. Columnar or wall-shaped diapirs (Fig. 1a) can be considered as ductile flows (e.g. of salt) along 3D pipes or 2D channels of ductile materials (e.g. clastic sediments). The denser country rocks sink into the deep layer of salt driving it upward along a different pressure gradient. This counterflow is a special case in the sense that it is asymmetric and along a material boundary that is visible in the usual reference frame for shear zones (Fig. 1b). I want to do the same for symmetric counterflow boundaries between initially identical materials without being specific about the boundary conditions that introduce the counterflow boundary outside the usual reference frame (see Fig. 1c and d).

By replacing my counterflow boundary by a change in sign of velocity, Sonder misses the point that deformation can generate new geological boundaries out of nowhere. Just as shear of brittle rocks can generate spontaneous new slip boundaries called fractures, I assumed that shear of ductile rocks can generate spontaneous new no-slip boundaries that I call counterflow boundaries. Whatever the *driving* forces, I still consider that natural *S* curves record the retarding forces that develop across two boundary shears, one on either side of a single shared no-slip boundary. (I should have stuck to reference frames and drawn my original fig. 2 as Fig. 2 here.)

I defend here my approach in Talbot (1999) on the sole basis of empirical fits between one or other the curves in a particular set (Fig. 2) with displacement curves either side of ductile shear zones in silicate rocks with very different mineralogies (and ages) deformed in a wide range of environments over an enormous range of scales. Because these fits are on scales much larger than the molecular mechanisms that control deformation mechanisms, I consider these empirical fits to indicate a rheological factor more universal

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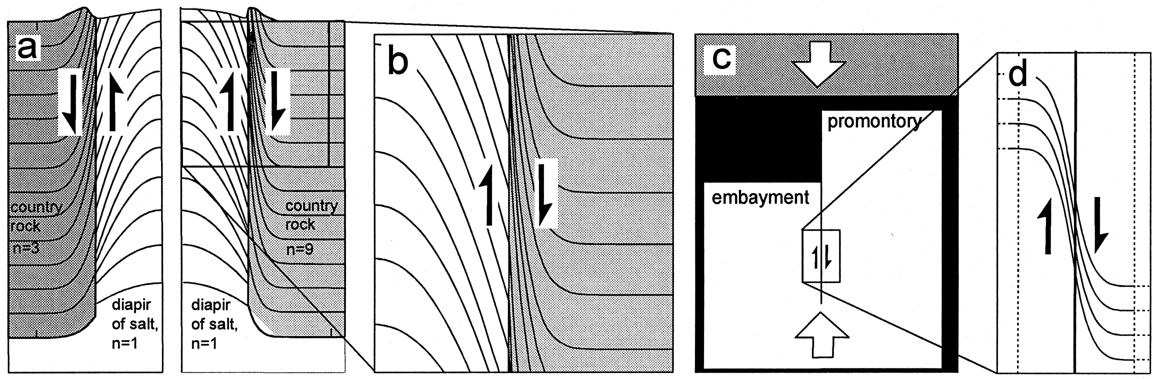

Fig. 1. (a) Boundary shears on either side of diapiric contacts illustrate that at least some counterflows can be driven by different pressure gradients either side of no-slip counteflow boundaries. (b) This no-slip counterflow boundary was generated outside the usual reference frame used for shear zones but is imported to account for the change in sign of retarding forces across it. (c) A counteflow boundary develops in the southern continent (white) after the promontory is sutured to the northern continent (grey). Identical rocks are retarded in two (symmetric) boundary layers along a shared no slip counterflow boundary imported into this reference frame.

than grain size, water content or temperature and attributed them to the general rheological description of *n*. Since Talbot (1999), I have found that the same curves fit experimental shear zones in pseudoplastic polymers in which changes in water content, grain size and temperature are irrelevant (Talbot, in prep).

The different approaches adopted in Talbot (1999) and Sonder (2000) could both have elements of truth. I was trying to account for the localisation of strain by introducing a new boundary to a general class of flow in a general class of rheologies. Flow retardation along a single counterflow boundary localises strain in two boundary shears to degrees dependent upon the *n*-value(s) of the fluids on either side. Neglecting my flawed dynamics, I showed empirically that constant or variable syn-shear *n*-values can be constrained from the geometry of S or J curves developed in natural counterflows. Sonder (2000) then goes on to show how particular strain weakening mechanisms across a single shear zone can account for the same n values specified by the shapes of the S or J curves.

In summary, I apologise again for failing to find the correct dynamic formulation for a process (different from that treated by Sonder, 2000) whereby strain gradients across *two* coupled shear zones are attributed to new boundary conditions that can localise a wide range of weakening processes to a degree expressed by *n*, the stress sensitivity of the strain rate. I therefore encourage readers to succeed where I failed.

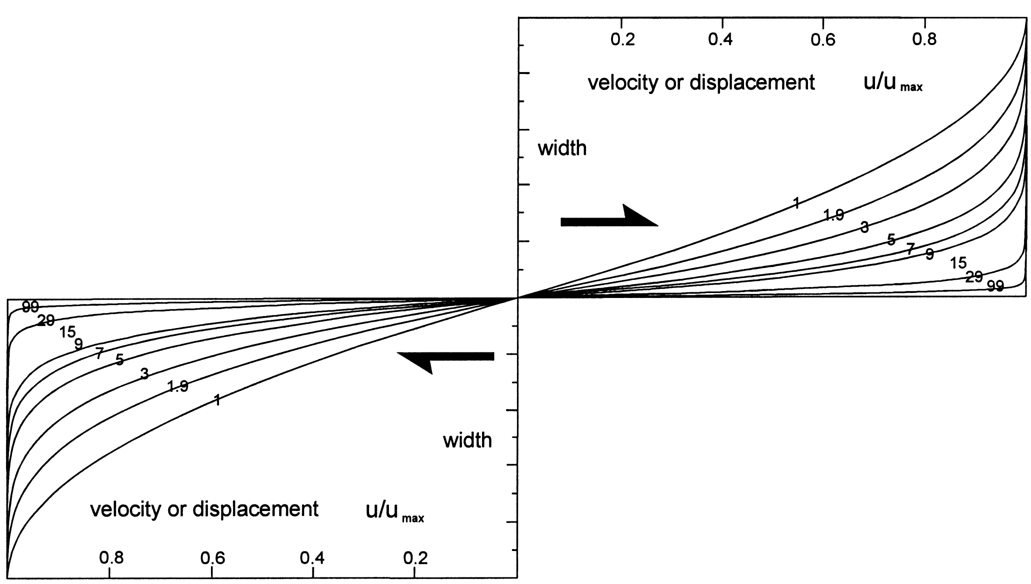

Fig. 2. This rearrangement of Turcotte and Schubert's (1980) curves for channel flow fits a wide range of shear zones in rocks. The central horizontal axis represents a no-slip (counterflow) boundary generated outside this reference frame and the upper and lower axes indicate where the retardation effects cease across each boundary layer.

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