Heterogeneous hydrofracture development and accretionary fault dynamics: Comment and Reply

COMMENT

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Brown et al. (1994) presented valuable new experimental data concerning the variation in permeability of muddy shear zones during progressive deformation and consolidation. The results indicate that permeability is decreased during both progressive shearing and consolidation, suggesting that shear zones commonly observed at the bases of accretionary prisms are not likely to serve as fluid conduits. Recognizing that their results present somewhat of a paradox because observations indicate long-distance fluid transport along the decollement of some accretionary wedges, Brown et al. (1994) developed a model for fluid expulsion involving "hydrofracture networks" that are heterogeneously distributed along the base of an accretionary prism. Confusion arises because it is not clear if this "network" results as a consequence of (1) compression-driven dilatancy (e.g., Brace et al., 1966), (2) dilation of existing fractures (e.g., Sibson, 1981), or (3) natural hydraulic fracturing (e.g., Engelder and Lacazette, 1990). Regardless of the identity of these crack networks, Brown et al. (1994) promulgated the mistaken impression (e.g., Lorenz et al., 1991) that a simple effective stress calculation can predict the pore-pressure increase [ΔP_p = total stress (S) − pore pressure (P_p)] necessary to initiate natural hydraulic fracturing. This impression is incorrect because, as a consequence of poroelastic behavior within rock, total horizontal stresses increase with increasing pore pressure. The purpose of this Comment is to point out the appropriate method for the analysis of natural hydraulic fracturing.

Brown et al. (1994, p. 261) argued that reduction in horizontal effective stress in an accretionary wedge "constrains any open system of hydrofractures to develop subparallel to the free surface." Although a tensile effective stress condition is present during both fluid-driven fracture propagation and dilation, the approach of Brown et al. (1994) is inappropriate because all crack-propagation phenomena, including natural hydraulic fracturing, must be analyzed with a total stress criterion. In fluid-saturated, porous media under the uniaxial strain conditions explicit in Brown et al.'s (1994) model of an accretionary wedge, the total horizontal stress changes as a function of pore pressure, P_p, according to:

$$S_h = \frac{\nu}{1-\nu} S_\nu + \frac{1-2\nu}{1-\nu} \alpha P_p, \quad (1)$$

where S_ν is the total vertical stress, ν is the Poisson ratio under drained conditions, and α, the Biot coefficient of effective stress, is <1 for most lithified rocks. This equation defines a reference stress state in which, in the absence of a tectonic stress, the minimum principal stress is horizontal (Engelder, 1993). Whereas it is true that the reduction in horizontal effective stress falls below the rate of vertical effective stress reduction as pore pressure rise, the total horizontal stress does not necessarily exceed total overburden stress when pore pressure exceeds the least principal stress (Engelder and Lacazette, 1990), a point overlooked by both Lorenz et al. (1991) and Brown et al. (1994). This is important because mode I fractures are constrained to propagate normal to the minimum principal *total* compressive stress.

The orientation of principal stresses near the bases of accretionary wedges is currently debated; some workers argue for subhorizontal minimum principal stress (e.g., Fisher and Byrne, 1987; Byrne and Fisher, 1990), and others argue for subvertical minimum principal stress (e.g., Brown et al., 1994). If a subvertical minimum principal stress is present as in a thrust-fault regime, then the results of Brown et al. (1994) are in agreement with those derived from a total stress criterion. This occurs because neither horizontal tectonic compressive stress nor poroelastically derived stress influences S_ν, which remains the minimum principal stress during overpressuring or deformation, thus constraining hydrofracture propagation to the horizontal plane. However, if the minimum principal stress is subhorizontal, an effective stress criterion fails because it does not account for the influence of P_p on S_h. When the minimum principal stress is subhorizontal under normal P_p, the total stress criterion favors vertical crack propagation; special conditions are required for the formation of horizontal fractures. Among these conditions is that α must be close to one, as is the case for mud. When α is close to one, even though S_h may initially be the minimum principal stress, increases in pore pressure may cause S_h to exceed S_ν. In this situation, horizontal natural hydraulic fractures may occur in an accretionary wedge even in the presence of a slight additional horizontal compressive tectonic stress.

Although the results presented by Brown et al. (1994) seem reasonable, we take exception to their use of effective stress in analyzing natural hydraulic fracturing. We do not discount the utility of effective stress analyses in describing the dilation of existing *horizontal* fractures under abnormal pore pressures (e.g., Sibson, 1981). However, dilation of existing interconnected cracks and fluid-driven crack propagation are two different phenomena. Analyses of "hydrofracture dilatancy" of existing cracks using an effective stress criterion (e.g., Sibson, 1981) are successful only when the tectonic stress state is one in which the minimum principal total stress is vertical, largely because S_v, unlike S_h, does not change with increasing pore pressure. The total stress criterion we advocate does not have such limitations. The lack of constraint on the reference stress state in accretionary wedges dictates use of a total stress criterion.

As a final point concerning Brown et al. (1994), we note an error in their equation relating a change in horizontal effective stress to a change in pore pressure. The correct equation for change in horizontal effective stress is:

$$\Delta \overline{S_h} = \alpha \Delta P_p = \frac{3(\nu_u - \nu)}{(1 - 2\nu)(1 + \nu_u)B} \Delta P_p, \quad (2)$$

where ν_u is the Poisson ratio for undrained conditions and B is the Skempton ratio (Kümpel, 1991).

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REPLY

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The brevity with which we needed to present our argument in *Geology* appears to have led Fischer and Engelder to misinterpret our comments on hydrofracture propagation. In the basal decollement of the Barbados wedge we are dealing primarily with the dilation of preexisting shear zones in a "relatively" weak and poorly lithified clay-rich sediment (~80% clay). We do not think that compression-driven dilatancy (i.e., Brace et al., 1966) can be very significant in these clay-rich lithologies. Such processes may, however, be more significant at seismogenic levels located at far greater depths.

Fischer and Engelder suggest that we had not considered total stresses when assessing whether growth of open vertical hydrofracture fracture systems could grow in response to leakage of elevated pore pressures to the laterally confined wall regions immediately around the hydrofractured parts of the decollement zone. This is not the case. We stated that "elastic swelling of the fault-wall sediments . . . will preferentially intensify the horizontal compressive stresses and prevent vertical hydrofracture development" (Brown et al., 1994, p. 261). This statement is consistent with a total stress criterion because, for example, the horizontal effective stress will fall with a pore-pressure increase. Fischer and Engelder imply that Lorenz et al. (1991) did not address the issue of hydrofracture propagation in terms of total stress. However, Lorenz et al. used the same total horizontal stress equation that Fischer and Engelder present as their equation 1. It is from this total-stress equation that we derived the equation we used to illustrate the change in horizontal effective stress in our paper. The total horizontal-stress equation for conditions of no lateral strain is given by (Lorenz et al., 1991)

$$\sigma_h = \sigma_\nu\left(\frac{\nu}{1-\nu}\right) + \alpha P\left(1 - \frac{\nu}{1-\nu}\right). \quad (1)$$

Rearranging this equation into a physically more meaningful form gives

$$\sigma_h = (\sigma_\nu - \alpha P)\left(\frac{\nu}{1-\nu}\right) + \alpha P. \quad (2)$$

From equation 2 it can be seen that the total horizontal stress is the product of the fluid pressure and the component of effective vertical stress that is transmitted laterally through the sediment framework. From the total horizontal stress equation, the change in total horizontal stress $\Delta\sigma_h$ with change in pore fluid pressure for conditions of no lateral strain is then given by

$$\Delta\sigma_h = \alpha \Delta P\left(1 - \frac{\nu}{1-\nu}\right), \quad (3)$$

and, on the basis of the total-stress equation and after subtracting the pore-fluid-pressure term, the change in effective horizontal stress $\Delta\sigma'_h$ with change in fluid pressure is given by

$$\Delta\sigma'_h = \alpha \Delta P\left(\frac{\nu}{1-\nu}\right). \quad (4)$$

Fischer and Engelder imply that we have incorrectly omitted the poroelastic parameter α from our equations. However, under undrained conditions, the value of the poroelastic parameter α (defined in equation 2 of Fischer and Engelder) is unity, because in poorly lithified clay-rich sediments, Skempton's parameter $B = 1.0$ and the undrained Poisson's ratio $\nu_u = 0.5$. Note that when $\alpha = 1.0$, our equation 4 is the same as the equation we used in Brown et al. (1994). It appears that, through some oversight, only part of the equation for the change in horizontal effective stress with change in fluid pressure is presented in Fischer and Engelder's Comment.

In Brown et al. (1994) we referred primarily to the overlying wedge where, in a thrust system, the total and effective horizontal stresses are greater than the vertical stresses. In this case we do not see the relevance of Fischer and Engelder's general concern; it would indeed be difficult for hydrofractures to propagate vertically upward from the decollement to allow fluids to escape by fracture flow through the wedge. In addition as we stated (Brown et al., 1994, p. 261) "elastic swelling of the fault-wall sediments . . . will preferentially intensify the horizontal compressive stresses and prevent vertical hydrofracture development" in response to any local leakage of fluids. Our statement is naturally referring to the *total* horizontal stresses. In citing the 1987 Fisher and Byrne and 1990 Byrne and Fisher references, Fischer and Engelder are, we presume, referring to the probability that the minimum stress is initially close to horizontal and the maximum stress is vertical in the sediments *beneath* the decollement. We did not have space to directly address this aspect in our paper but, nonetheless, vertical hydrofractures are also unlikely to develop in this environment (unless the condition of no lateral strain is relaxed). This is because as leakage occurs and pore pressures rise in the underthrust sediments, the orientations of the maximum and minimum principal total and effective stresses will reverse before the value of total horizontal stress minus the pore-fluid pressure equals zero and vertical hydrofractures can begin to form. As a consequence, propagating hydrofracture systems will tend to be trapped in the decollement zone, and leakage from them via open vertical hydrofractures will be severely limited. Furthermore, our ring-shear experiments suggest that, together with any cementation, deformation will strongly reduce vertical equivalent permeabilities. Leakage of fluid into the surrounding regions via intergranular flow will thus also be very limited. It is for this reason that hydrofracture systems can propagate from the source regions many tens of kilometres along the decollement through regions of the wedge that, while overpressured, have fluid pressures that are generally below lithostatic levels.

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