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REPLY

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I thank Buck [this issue] for the opportunity to discuss further the mechanical origin of crustal-scale low-angle normal faults. Buck raises three main objections: (1) the magnitude of basal shear traction (10-50 MPa) selected in my calculations is too high, (2) the magnitude of shear stress predicted in the model with low basal shear traction (10 MPa) is too low to initiate low-angle normal faults, and (3) the predicted tensile stress near the surface in the model is too high for rocks to sustain. Because the concept of shearing at the base of the upper crust is essential to my models, I will address this point first.

MAGNITUDE OF BASAL SHEAR TRACTION

On the basis of recent geological and geophysical studies of metamorphic core complexes in the U.S. Cordillera, I proposed that a subhorizontal shear traction applied at the base of the brittle upper crust could be responsible for the formation of mid-Tertiary, crustal-scale low-angle normal faults in the North American Cordillera. I assumed that the magnitude of the basal shear traction is between 10 and 50 MPa. Buck considers these magnitudes too high because the widespread mid-Tertiary volcanic activity implies that the lower crust was "hotter" than that of the present Basin and Range and therefore quite weak. As I stated [Yin, 1989, p. 473], this selection of the values of basal shear traction in my calculations (10-50 MPa) was based on an investigation of stress magnitude during the formation of mid-Tertiary quartzose mylonitic rocks in Cordilleran core complexes conducted using experimentally calibrated quartz grain-size paleopiezometers [Hacker et al., 1988; Yin et al., 1988; Hacker et al., in press]. Results of these studies suggest that shear stress during the formation of the mylonitic rocks was between 15 and 50 MPa. Because the mylonitic rocks in the footwalls of major low-angle normal faults developed at middle-crustal level and were later transported upward to the surface by low-angle normal faulting [e.g., Davis et al., 1986; Davis, 1988; J. L. Anderson, 1989; Snoke and Miller, 1988] (also see discussions in the introduction of Yin [1989]), these estimated stress magnitudes represent the stress conditions in the plastically deformed middle and lower crust during the development of low-angle normal faults. The combined results of the paleopiezometeric and kinematic studies of the mylonitic rocks in core complexes form the basis for my choosing a basal shear traction of 10-50 MPa.

SHEAR STRENGTH OF THE CRUST

Buck suggests that the shear stress predicted for the formation of low-angle normal faults in the model of low shear traction (10 MPa; Figure 6b of Yin [1989]) is

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too low based on Brace and Kohlstedt's [1980] calculations of crustal shear strength extrapolated from laboratory measurements. Buck's objection relies on Brace and Kohlstedt's calculations that the shear stress required for frictional sliding at a depth of 10 km is between 80 MPa (hydrostatic pore fluid pressure) and 120 MPa (zero pore fluid pressure). These stress calculations are, however, based on two major assumptions. First, it is assumed that the directions of the three principal stresses are vertical and horizontal throughout the crust so that the vertical stress is equal to lithostatic pressure. As discussed in my paper, this assumption is not warranted because the principal stress directions might be rotated, for example by shearing at the base of the upper crust induced by flow in the middle and lower crust. If we hold this assumption, then horizontal faults should never develop because shear traction on a surface perpendicular to a principal stress direction is always zero. It is this assumption that renders the Andersonian fault theory [Anderson, 1942] unable to explain the mechanical origin of crustal-scale low-angle normal faults. The second assumption in the calculations of the crustal shear strength is that the pore fluid pressure within the entire crust is known. Brace and Kohlstedt [1980] assumed that the pore fluid pressure ratio is constant throughout the crust. They examine two special cases : (1) hydrostatic pore fluid pressure and (2) zero pore fluid pressure. However, many other pore fluid pressures are possible. Brace and Kohlstedt [1980, p. 6251] were well aware of this uncertainty and stated: "what is known about pore fluid pressure level at depth? Unfortunately, almost nothing, so that this parameter is totally unconstrained at this time."

To further the discussion, let us assume that principal stresses are vertical and horizontal and that the maximum compressive stress is vertical and equal to the lithostatic pressure. The shear strength of the crust can be calculated using Brace and Kohlstedt's equation (3). If the pore fluid pressure ratio equals 0.8-0.9, the shear strength of the crust at a depth of 10 km is 21-11 MPa, respectively (crustal density of 2.8 g/cm^3). The latter is close to what is predicted by the model with the lowest basal shear traction (10 MPa; Figure 6b of Yin [1989]) at a depth of 10 km near the region where low-angle normal faulting is predicted. The influx of deep-level, magmatically-derived fluid from the lower crust and upper mantle during the voluminous, widespread mid-Tertiary volcanism in the U.S. Cordillera [Coney and Reynolds, 1977; Coney, 1980; Dickinson, 1981; Zoback et al., 1981] may have generated high pore fluid pressure and weakened the brittle upper crust. Thus the selected high pore fluid pressure ratios above are not unreasonable. Note that rotation of the principal stresses from horizontal and vertical directions was completely ignored in the above calculations. If the rotation is considered, a lower value of pore fluid pressure is required. If both the effect of high pore fluid pressure and rotation of the principal stresses are considered, then the predicted shear stress in the model with low basal shear stress (Figure 6b of Yin [1989]) can still initiate low-angle normal faulting.

Buck noted that low-angle normal faults are always predicted in the places where the model shear stress is the smallest. From this point he inferred that the high-angle fractures would be the preferred sites for fault slip. It is true that the region with higher predicted shear stress is more likely to undergo faulting than the region with lower shear stress. However, rock will fail as long as the shear stress exceeds the shear strength of the rock (see discussions by Hafner [1950]). As discussed above, the combined effect of high pore fluid pressure and the rotation of principal stresses is that the predicted shear stress in the model of low basal shear traction is sufficient to initiate faulting in the region where low-angle normal faults are predicted.

TENSILE STRENGTH OF ROCKS NEAR THE SURFACE

Buck criticized that all the models resulting low-angle normal faults predicted tensile shear stresses at the surface, and that in the model with high basal shear traction (50 MPa; Figure 7c of Yin [1989]), the tensile stress is too high for rocks to sustain. This is not a problem because once tensile stress exceeds the tensile strength of rock, extension fractures will occur. Dike swarms, clastic dikes, and mineral veins are not uncommon features in the upper plates of major low-angle normal fault systems in the U.S. Cordillera [e.g., Frost and Martin, 1982]. They could be explained as the result of the tensile stress induced by the basal shear traction.

Buck is correct in stating that the occurrence of extension fracture (shear fracture also) will alter the stress field and that the new boundary conditions across these discontinuous surfaces should be considered. The model of Yin [1989] does not address stresses in the crust after through-going low-angle normal faults formed, "the model presented here predicts only the initiation of faulting, because the Coulomb fracture criterion is assumed" [Yin, 1989, p. 480]. However, the low-angle and high-angle normal shear fractures produced by basal shearing in the initial stage of formation of a low-angle normal fault system should have played an important role in controlling its later evolutionary history.

SUMMARY

The magnitude of the basal shear traction assumed in my calculations corresponds well to the best current estimates of stress magnitude in the plastically deformed middle crust of mid-Tertiary Cordilleran metamorphic core complexes. The predicted tensile stress near the surface explains the development of extension fractures in the upper plates of major low-angle normal faults.

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