FORUM

Raising the Colorado Plateau: Comment and Reply

COMMENT

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McQuarrie and Chase (2000) proposed three tests for their novel model. First, that it is possible to account for the elevation of the Colorado Plateau in their model by reasonable variation of crustal thickness. Second, that mechanical parameters required of their model assume reasonable values. Third, that geological evidence supports their model.

The first and second proposed tests are relatively weak because they involve returning to examine the parameters used to build their model in the first place, and because competing models would pass these tests as well. Their third proposal provides a substantive test, but one cannot apply it without taking their model to its ultimate conclusions.

The crucial test requires a prediction of how upper crust behaves in their model, which is something they did not do. In Figure 1 here, I have indicated two planes by dashed lines in the cross section of the Colorado Plateau. The horizontal plane (A) lies at the interface between upper crust and the postulated Poiseuille channel through which the ductile middle crust (shaded region) flows. The vertical plane (B) is an arbitrary section of the upper crust on which to make a calculation of the stress needed to maintain the upper crust in equilibrium. By calculating approximate stress values on these planes, we may further the analysis of McQuarrie and Chase's model.

McQuarrie and Chase (2000) referred to the upper crust of their model as having no flexural rigidity, meaning that it can be bent upward to allow ductile injection without resistance. However, by using a model of Poiseuille channel flow, they imply that the upper crust has rigidity to the flow in a longitudinal direction and must therefore support shear stress on the wall of the channel. The shear stress here is by definition $\tau = \mu \partial u/\partial y$, where μ represents dynamic viscosity and u is the horizontal velocity of ductile material. If I set my coordinate system in a way that $y = 0$ represents the center of the ductile channel, then the appropriate magnitude of $\mu \partial u/\partial y$ equals $-\mathrm{K}h/2$. I can calculate the constant of proportionality (K) from the pressure gradient that McQuarrie and Chase document, or I can calculate what it must be in order to fill the channel with material in a span of 35 m.y. In SI units, the constant's value lies between 600 and 750. Since $h/2$ is 7500 m, the resulting shear stress is between 4.5 and 5.5 MPa. This is similar in magnitude to the shear stress at a transform plate boundary, and one ought to see the results of such a stress reflected in deformation and faulting of the overlying rock. To my knowledge, no such deformation occurs.

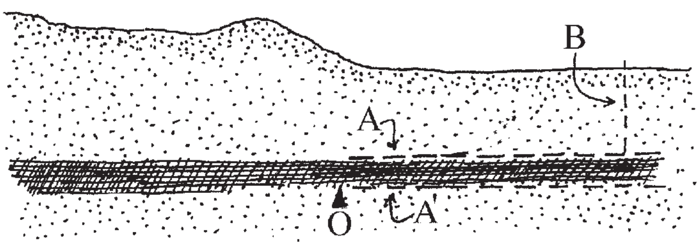

Figure 1. Hypothetical cross section that shows plateau and uplifted region. Change in elevation provides pressure gradient to drive rightward flow of ductile material (shaded) in Poiseuille channel, lines A and A′ denoting its bounding planes. Dashed lines A and B indicate planes on which to calculate relevant stress from equilibrium and method of sections. Because flow of viscous material within channel leads to shear stress on its bounding planes, a rigid plateau must resist normal stress on B and shear stress on A without deformation.

Next, apply this result to the arbitrary section labeled B. For each distance increment of 15 km to the east of the origin on my diagram, this section will have to support an incremental average normal stress of 4.5 MPa to maintain horizontal equilibrium. The Colorado Plateau is 200–300 km in east-to-west dimension depending on location. Thus, to maintain equilibrium at the section requires an average normal stress that grows with distance to a maximum value of ~100 MPa. This is nearly equal to extreme point estimates of normal stress on a convergent plate boundary. Thus, in response to the ductile flow, one should see new thrust faults, or at least the rejuvenation of existing low-angle faults, and the piling up of crustal material within and beyond the Colorado Plateau. In appreciation of this, McQuarrie and Chase (2000) proposed that Laramide mountain building east of the Colorado Plateau is precisely this response. However, Laramide uplifts occur 500 km to the east of the Sevier fold belt in places, and the thin upper crust of the Colorado Plateau must have then resisted gargantuan normal forces without deformation to transmit these forces to the Laramide uplifts. Moreover, the uplifts occur with high-angle reverse faults, which are better suited to relieving vertical or nearly vertical stresses, while horizontal stress seems more suited to producing low-angle thrusts.

In addition to normal stress, the section (B) must provide shear stress to maintain equilibrium against rotation of crustal blocks above the ductile flow. The magnitude of this stress depends on geometry and dimension of hypothetical crustal blocks, but there is no pervasive, consistent tilting of crustal materials on the Colorado Plateau in any case.

Although this represents weak evidence on the subject, no recent uplift following this ductile flow mechanism occurs in the western United States. The Kaibab Plateau, Utah's high plateaus, western Wyoming, and the Yellowstone region are examples of uplifts that have occurred without any associated high terrain nearby to force a mid-crustal ductile flow.

McQuarrie and Chase's (2000) model, at least in its current form, seems a less likely mechanism of uplift of the Colorado Plateau than does a modification of the underlying mantle or lower crust from below.

REFERENCE CITED

McQuarrie, N., and Chase, C.G., 2000, Raising the Colorado Plateau: Geology, v. 28, p. 91–94.

REPLY

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Kilty's main objection to raising the Colorado Plateau via crustal flow is what he might call the failure of a crucial test: verifying the predicted implications of the model for the upper crust. We welcome the opportunity to defend the necessity of the tests we proposed and also to explain how the "crucial test" that Kilty proposes strengthens, rather than weakens, our model of Colorado Plateau uplift.

The first hurdle for crustal thickening mechanisms for the uplift of the Colorado Plateau is viability. We evaluated the viability of plateau uplift by intracrustal flow by first seeing if it is possible to account for changes in elevation by reasonably varying crustal thickness, and second, by evaluating the necessary viscosity and topographic gradients. The third "test," providing geologic evidence to support intracrustal flow, would show the admissibility of the process.

Evaluating the strength of the upper crust is important for determining viability. Although we do not disagree with Kilty's approximate methods for evaluating stresses in the upper crust, we feel that his conclusions are inconsistent with the geology of the Laramide and Colorado Plateau region. Kilty concludes that the horizontal shear stresses (4.5–5.5 MPa) and the consequent normal stresses (up to 100 MPa) predicted by channel-flow calculations are "gargantuan," and thus significant deformation should be reflected in the geology. Our response to this conclusion is twofold. (1) The magnitude of the stresses calculated by Kilty is not excessive, but rather agrees nicely with the magnitude of regional stresses in contractional areas (Zoback et al., 1993; Vernik and Zoback, 1992). (2) We reiterate our previous points that the Colorado Plateau did not need to resist "gargantuan forces without deformation," but, rather, the crustal flow essentially decoupled the upper crust from the lower crust, provided a mid-crustal detachment, and allowed for the eastward propagation of contractile strain in the form of Laramide uplifts (McQuarrie and Chase, 2000, p. 93), many of which are low angle (e.g., Brewer et al., 1982). This contractile strain is in part a result of the eastward propagation of the Cordilleran fold-and-thrust belt and in part a result of the shear stress associated with channel flow. The eastward progression of Laramide uplifts is best documented in the Wyoming region (Brown, 1988) but Laramide age, basement-cored uplifts are pervasive throughout the Colorado Plateau to the Front Range. This removes any need for the Colorado Plateau proper to remain undeformed (e.g., Davis, 1999). We proposed that the topography that exists now in the western United States is a result of the formation and evolution of a late Cretaceous high-elevation plateau. The eastward growth of the plateau, through the propagation of mobile crust from the hinterland of the orogen to the foreland, uplifted the Colorado Plateau and the Wyoming and Montana Laramide provinces. It is the unique coexistence of ductile extension in the hinterland, eastward evolution of the frontal fold-and-thrust belt, and disruption and dissection of the foreland by Laramide basement-cored uplifts that support a crustal flow model for uplift of this region in the Late Cretaceous and early Tertiary (McQuarrie and Chase, 2000). We emphasize that Utah's high plateaus (including the Kaibab, Wasatch, and Aquarius) and parts of Arizona, New Mexico, and Colorado are included in the "Colorado Plateau," and we underscore that this process is not limited to the Colorado Plateau but also includes much of the Wyoming and Montana region as well. This implies that the general age of elevation in all of these provinces is Laramide. However, the broad topographic uplift associated with the Yellowstone hotspot seems to be a result of an entirely different process (Pierce and Morgan, 1992) and perhaps is the only young, major uplift in North America.

The strength of our model for raising the Colorado Plateau by intracrustal flow is that it combines many of the enigmatic features associated with the Cordilleran orogen into one cohesive model to explain the topographic evolution of the western United States. This aspect is not present in previous models of Colorado Plateau uplift.

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