the range. In this view, the Oak City Formation would be re-interpreted to include only the east-dipping, syntectonic conglomerate, large-rock avalanches, and other minor sediments. All of the exposed Tertiary units from the crest of the range to west would thus be mid-Miocene in age and younger.

In conclusion, evidence for major low-angle, top-to-the-west fault movement along the western side of the range and new evidence for south-to-the-west movement on the south side of the range are compelling and consistent with the existence of the Sevier Desert detachment suggested by subsurface information.

Fracture-controlled magma conduits in an obliquely convergent continental magmatic arc: Comment and Reply

COMMENT

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Using the orientation of anisotropy of magnetic susceptibility (AMS) ellipsoids, Tobisch and Cruden (1995) developed a provocative model for the ascent/emplacement of two nested plutons within the central Sierra Nevada batholith, California. In doing so, they made two important but controversial assumptions: (1) that the geometry of AMS ellipsoids, which are coaxial with magmatic fabrics in the Dinkey Creek and Bald Mountain plutons, is the result of magma flow parallel to the foliation plane and in the direction of the magnetic (magmatic) lineation, and (2) that ascent of these two magmas occurred via subvertical north-south-trending planar conduits that can be imaged by the geometry of the magnetic lineations.

Before these assumptions can be evaluated, we think there are three issues that need discussion: how the authors determined (1) magma flow paths from fabric patterns, given that these geometric patterns may result from a variety of different types of flow, (2) the relative timing of fabric formation, and thus (3) the cause of magmatic fabric development, given that magmatic fabrics may result from flow during ascent, emplacement, regional strain, or internal magma chamber processes. Below we address each of these issues with regard to the data presented by Tobisch and Cruden in the hope that we will encourage the authors to more fully explain the steps in their reasoning that lead to their conclusions.

Issue 1: Magma Flow Paths and Fabric Geometry. Tobisch and Cruden interpret magmatic foliations as indicators of flow parallel to the foliation in the direction of the lineation. This is a kinematic interpretation of geometric data and without additional data is but one of a number of possible interpretations of the fabric patterns in the Dinkey Creek and Bald Mountain plutons. For example, Mackin (1947; see Bateman, 1992, p. 36) noted three different types of non-uniform flow that may control the geometry and orientation of magmatic fabrics: acceleration, deceleration, and velocity gradient flow. Acceleration flow occurs where magma is funneled from a wide region into a narrow channel with increasing flow velocity. Constrictional fabrics develop and anisotropic minerals will attempt to align themselves parallel to the x axis of the finite strain ellipsoid. In other words, at high strains acceleration flow will produce lineations parallel to the flow direction. Deceleration flow involves flow of magma from a narrow channel into a wide region, causing the magma to decelerate as it exits the channel. Deceleration flow will be characterized by fabrics that approach an oblate shape with their XY planes oriented perpendicular to the flow direction. Velocity gradient flow involves drag of the magma along some high-viscosity boundary material such as a chamber wall or an inward-migrating crystallization front and typically forms triaxial fabrics initially at angles to flow planes and directions.

Given these possible flows, interpreting magmatic foliations as flow planes requires two pieces of information: (1) the geometry of the flow plane and (2) the kinematics of displacement of particles within that plane. AMS analyses establish the geometry of magmatic fabrics within the plutons that are approximately coaxial with magmatic fabrics based on image analysis and outcrop observations (Tobisch and Cruden, 1995). However, no information regarding the kinematics of flow is inherently provided in the AMS analysis, and no microstructural or other kinematic information was provided by the authors to evaluate their conclusions. Thus, it is unclear to us how Tobisch and Cruden determined the flow patterns shown in their Figure 5 and how they determined that magma was entering the chamber along their proposed fracture conduits.

Issue 2: Relative Timing of Fabric Formation. Magmatic fabrics in plutons may be caused by nonuniform flow into a growing chamber, regional strain imparted on a crystallizing pluton, and internal processes such as convection, magma replenishment by addition of new melt, or discharge during eruption (Paterson and Vernon, 1995). Thus, it is necessary to establish the timing of formation of fabrics in order to relate them to a particular process. Tobisch and Cruden in their Introduction make reference to the idea that emplacement-related flow may mask earlier patterns of ascent, but later in the paper they use fabric patterns to infer ascent (their Fig. 5). Nowhere is the timing of fabric formation discussed. Thus we are again puzzled about how they concluded that the foliation and lineation patterns provide information about ascent or emplacement.

Issue 3: Cause of Magmatic Fabrics. On the basis of the lineation data, Tobisch and Cruden jump directly to the conclusions that (a) flow of magma occurred parallel to the lineation, (b) magnetic lineations converge on two feeder zones, and therefore (c) the orientation of fabrics in these plutons was caused by flow via the planar feeder zones. Even if they could establish that flow occurred parallel to the lineation, we feel that the correlation between lineation data and the linear feeder zones is tenuous for the following reasons. (1) If feeder zones were imaged by the lineations it should be possible to contour these data according to plunge and observe a linear bulls-eye of where the feeder zones existed. In fact, the lineations plunge gently to steeply with a variety of trends, even near the proposed feeder zones. Furthermore, magmatic foliation data (Bateman, 1992, p. 36) display smooth curvilinear trends, particularly in the southwest lobe of the Dinkey Creek pluton, that crosscut the proposed linear feeder zone. (2) Magmatic foliations from the Dinkey Creek pluton (Bateman and Wones, 1972) show a gentle deflection along the western and southern margins of the Bald Mountain pluton, and locally this deflection is truncated by the Bald Mountain pluton. Although Tobisch and Cruden interpret the down-dip lineation data in this region to image a feeder zone (their Fig. 2), there are several equally permissible conclusions, one of

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which is that these data represent the downward return-flow of hot and mushy Dinkey Creek magma during emplacement of the Bald Mountain pluton. (3) Although no scale is given in Figure 5, comparison of Figures 2 and 5 indicates that they are extrapolating surface data to depths of ~5 km to infer the locations of the feeder systems. Given the complex fabric pattern at exposed levels, on what basis can such data be extrapolated to such depths?

To conclude, although measuring AMS has become an increasingly popular means of characterizing magmatic fabrics in plutons, these data only provide geometric information. Without timing and kinematic information, we are skeptical of the use of these data to discern the causes and kinematics of fabric development in plutons and hope that Tobisch and Cruden will clarify their datasets and the assumptions that led them to their conclusions.

REFERENCES CITED

REPLY
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We thank Yoshinobu and Paterson for the opportunity to further explain our model for the emplacement of the Bald Mountain pluton and its relationship to the surrounding Dinkey Creek pluton (Tobisch and Cruden, 1995). Their comment is based on three issues regarding the interpretation of foliation and lineation data, in our case derived from magnetic fabric analysis, in plutons. Yoshinobu and Paterson are correct in stating that the pattern of magmatic fabrics in a pluton may not have a unique interpretation and that these fabrics can form during emplacement, reorganization of magma within the pluton after emplacement, or tectonic deformation of the magma before it becomes fully crystallized. However, we argue below that some of their objections stem from an incorrect understanding of the physics of viscous flow and a somewhat skewed reading of our paper.

Issue 1. Yoshinobu and Paterson question our kinematic interpretation of magmatic foliation and lineation data, citing Mackin’s (1947) definition of “acceleration, deceleration, and velocity gradient” flow regimes. First, the terms acceleration and deceleration flow are misleading. They imply that the flows are inertial, which, given the high viscosities of felsic magmas, we consider to be unlikely under natural conditions. Second, Mackin’s first two flow regimes are inherently two-dimensional. The concepts of convergent and divergent flow are more appropriate, because they are explicitly three-dimensional and can be applied to creeping flows. Third, the classification of velocity gradient flow as a special case is also misleading. All natural, three-dimensional flows that result in a detectable fabric are characterized by velocity gradients. Yoshinobu and Paterson’s third flow regime is more appropriately referred to as progressive simple shear flow.

The relationships between velocity gradients, strain rates, and deviatoric stresses are fundamental to continuum mechanics (e.g., McKenzie, 1979). These basic mathematical relationships are used to determine the orientations of the principal finite strain axes in viscous flows (e.g., Cruden, 1990). Assuming that fabric elements can be correlated with the strain axes, modeling shows that in most cases the foliation plane lies <45° to the flow plane, and the lineation that it contains has the same azimuth as the particle movement path. The exception is when the flow is strongly divergent, as in the case of particles flowing toward and normal to a wall.

Under most situations, foliations and lineations therefore give a reasonable, if not exact, picture of the last increments of flow in the magma. Since most granitic rocks do not contain the types of kinematic indicator alluded to by Yoshinobu and Paterson, the actual directions of flow are indeterminate in most cases. The interpretation then relies on matching the observed structural and compositional patterns and age relationships to a dynamically and kinematically feasible model that best fits the data.

Our conceptual model for flow in the BMP during its emplacement (Tobisch and Cruden, 1995, Fig. 5) is based on an attempt to explain the following features: (1) the consistent, shallowly plunging northwest-southeast trend of the magnetic lineation as well as the generally moderate southeastward dips of the magnetic foliation; (2) the observation that in detail the contacts of the pluton conform to northwest and northeast trends, parallel to joints in the host rock (Dinkey Creek pluton) and the strike of foliations in the pluton; (3) the presence of shallowly dipping dikes of Bald Mountain pluton magma intruding the Dinkey Creek pluton; and (4) the north-south elongation of the pluton. The first three features may be explained by the upward and outward migration of magma into a strongly jointed host rock from a series of en echelon north-west-oriented vertical conduits. Host rock joints may have facilitated local roof lifting and subhorizontal flow, as well as providing guides for en echelon fracture propagation. The confinement of the en echelon feeders of the Bald Mountain pluton magma to a <2–5-km-wide, 10-km-long north-trending zone suggests that they were terminal fractures to a major north-south dike at depth. However, in the absence of additional evidence for sheeting in the Bald Mountain pluton, we acknowledge that this model is speculative and would welcome alternative explanations.

Issue 2. Yoshinobu and Paterson are concerned with the timing of the fabrics in the Bald Mountain pluton. Microstructural observations, using the criteria of Paterson et al. (1989), indicate that the fabrics in the pluton formed before it had crystallized completely. The presence of locally very shallow foliation dips in the Bald Mountain pluton and the complete absence of postcrystallization deformation features in the Dinkey Creek pluton immediately surrounding the Bald Mountain pluton rule out a regional tectonic origin for the fabrics. An origin due to flow caused by postemplacement thermal convection is possible, but conductive heat loss from such a small body was probably too rapid for the attainment of a supercritical Raleigh number. Yoshinobu and Paterson imply that we used the fabric pattern to infer information about ascent. In fact, in several places in our paper we state categorically that we interpret the fabric pattern in the Bald Mountain pluton to have formed at the site of emplacement (see above).
**CORRECTION**

Reduction of CO$_2$ during serpentinization of olivine at 300 °C and 500 bar: Correction


In our recent paper, we reported synthesis of an unusual morphologically distinct carbon-bearing phase to account for a depletion in dissolved CO$_2$ concentrations during our study. Subsequently, however, Dr. Satish Srivastava notified us that this “phase” strongly resembled pine pollen, which was later confirmed by palynologists at the University of Minnesota. Apparently, the pollen contamination was introduced in the course of filtration and drying operations that were used to prepare run products for analysis. These procedures were performed at a time coinciding precisely with the local release of pollen from pines in our area.

This correction actually simplifies the interpretation of the results, because the origin of the unusual “phase” was problematic. It was not predicted to form from thermodynamic relations. This does not affect the more important conclusion in our paper of coupled H$_2$ generation and slow conversion of CO$_2$ to CH$_4$, C$_2$H$_6$, and C$_3$H$_8$ during serpentinization. It is now likely, however, that the large loss in dissolved CO$_2$ observed during the experiment was caused by precipitation of amorphous carbon or graphite—a phase that was predicted to precipitate during the experiment based on fluid-mineral equilibria calculations and that was observed in trace amounts.

We thank Dr. Satish Srivastava for bringing this to our attention.

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