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Nucleation, growth and structural development of mylonitic shear zones in granitic rocks: Discussion

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The paper by Christiansen and Pollard (1997) presents a field study of the development of mylonitic shear zones in the Sierra Nevada batholith, California. We commend the authors for attempting to reconstruct the three-dimensional geometry of the shear zones in a unique area of excellent exposure. However, based on our field observations in the Mono Creek granite, we believe that some of the interpretations offered by the authors are hampered by not being fully acquainted with the relevance of ongoing work in the region or recent timing constraints (Tobisch *et al*., 1995). First, the sinistral shear zones are generally associated with major dextral shear zones (Sierra Crest shear zone system; e.g. Tikoff, 1994; Greene and Schweickert, 1995; Tikoff and Saint Blanquat, 1997), and have a conjugate orientation. Second, the association of sinistral shear zones and aplite dikes is not general, and the presence of aplite dikes is not necessary for sinistral shear zone development. We have the following specific comments.

1. The article fails to observe the occurrence of the Sierra Crest shear zone system, a series of batholith-scale dextral shear zones developed during emplacement of plutons along the youngest trend of magmatism within the batholith (Busby-Spera and Saleeby, 1990; Tikoff and Teyssier, 1992, 1994; Tikoff, 1994; Greene and Schweickert, 1995; Tobisch *et al*., 1995; Tikoff and Greene, 1997; Tikoff and Saint Blanquat, 1997; and multiple abstracts). In fact, the recognition of the Rosy Finch shear zone of orthogneiss within the Mono Creek shear zone lead to the definition of the Sierra Crest shear zone system (Tikoff and Teyssier, 1992). According to the map of the Rosy Finch shear zone (Fig. 1), the study by Christiansen and Pollard (1997) took place either on the edge or within the shear zone. Ignoring the Rosy Finch shear zone is at the detriment of the potential role it played in the development of the smaller sinistral shear zones, particularly given their spatial association.
2. The Mono Creek granite is one of the best documented examples of a syn-tectonically emplaced pluton. This conclusion has been reached through structural observation (Tikoff and Teyssier, 1992) and porphyroclast interaction modeling (Tikoff and Teyssier, 1994), in addition to detailed microstructural and Anisotropy of Magnetic Susceptibility (AMS) studies of the entire Mono Creek pluton (Saint Blanquat and Tikoff, 1997; Tikoff and Saint Blanquat, 1997). Tobisch *et al*. (1995) indicate that dextral deformation within the Lake Edison pluton must have occurred immediately after emplacement of that pluton and thus was ongoing during emplacement of the Mono Creek pluton. Therefore, it is impossible to accept the 'static' view of pluton emplacement of Christiansen and Pollard (1997, p. 1168–1170)—"Following crystallization of the Mono Creek Granite, the last phases of magmatic activity involved the emplacement of a series of aplite and pegmatitic dikes in various orientations." The microstructural studies combined with the AMS studies clearly show that deformation and magmatism proceeded together during the emplace-

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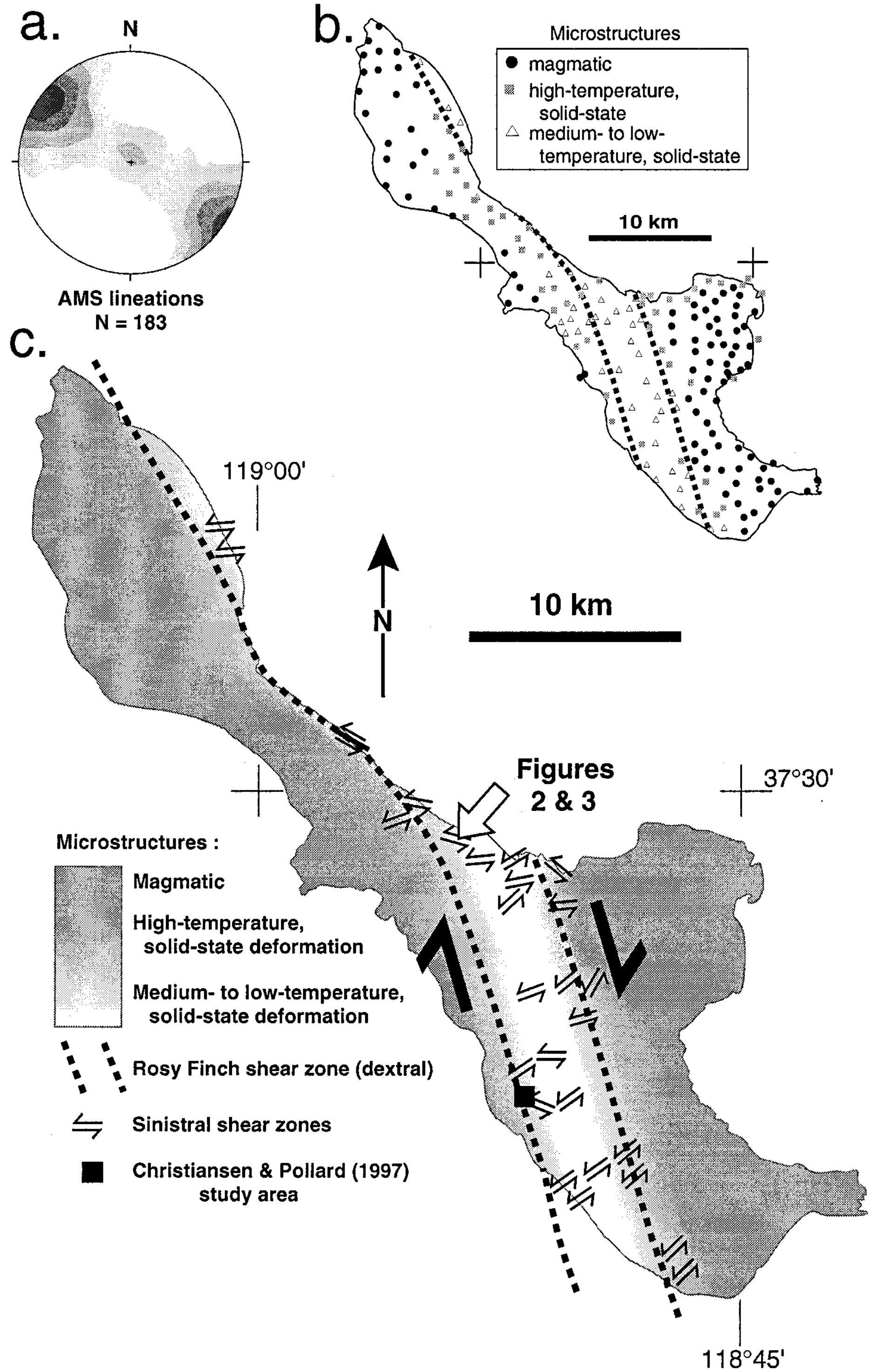

Fig. 1. Modified from Saint Blanquat and Tikoff (1997). (a) Stereonet of AMS (Anistropy of Magnetic Susceptibility) lineations indicating a dominantly shallowly-plunging orientation throughout the main body of the Mono Creek pluton and within the dextral Rosy Finch shear zone (RFSZ). (b) The position and microstructural characterization of the AMS sample locations. The combined microstructural and AMS studies suggest that shearing continued from magmatic to low-temperature solid-state deformation, indicating a complex relationship between deformation and magmatism. (c) Orientation and position of small-scale sinistral shear zones, which are associated with the dextral RFSZ. Sinistral shearing is generally ductile within the RFSZ and brittle at the edges of the RFSZ, though both brittle and ductile behavior occur locally within the RFSZ (Tikoff and Saint Blanquat, 1997).

ment and subsequent history of the Mono Creek granite (Fig. 1).

3. Despite the fact that dextral shearing initiated in the magmatic stage, the latest stages of dextral shearing occur under greenschist facies conditions, similar to conditions that occurred during development of the sinistral shear zones. The microstructural study of Saint Blanquat and Tikoff (1997)

demonstrates that the low temperature microstructures of the Rosy Finch shear zone are flanked by high-temperature, solid-state microstructures and, finally, magmatic microstructures (Fig. 1). In the field area of Christiansen and Pollard (1997), the sinistral shear zones clearly cross-cut higher-grade wallrocks. However, dextral shearing further east in the central part of Rosy Finch shear zone continued down to the same greenschist conditions typified by the sinistral shear zones. In this type of upper-crustal batholithic setting, the transition from high-temperature to low-temperature can occur within a short time. In addition, the large thermal gradients allow coeval development of kinematically-related ductile fabrics and mylonitic/brittle fabrics over short distances.

4. This highlights the importance of resolving the timing between the dextral and sinistral shearing in the Mono Creek pluton. While data do not exist for this pluton, there are sufficient data elsewhere to constrain the problem. The Lake Edison pluton (U/Pb on zircon age of 88 ± 1 Ma; Tobisch *et al.*, 1995) is adjacent to, and slightly older than, the Mono Creek granite (86 Ma from U/Pb on zircon; B. Carl, personal communication, 1996). Segall *et al.* (1990) report $^{40}Ar/^{39}Ar$ ages on muscovite at 79.2 ± 0.8 Ma, from sinistral fractures in the Lake Edison pluton, which are considered a minimum age (Christiansen and Pollard, 1997). The sinistral fractures in the Lake Edison pluton can be locally connected to the sinistral shear zones in the Mono Creek granite (Tikoff, 1994; Tikoff and Saint

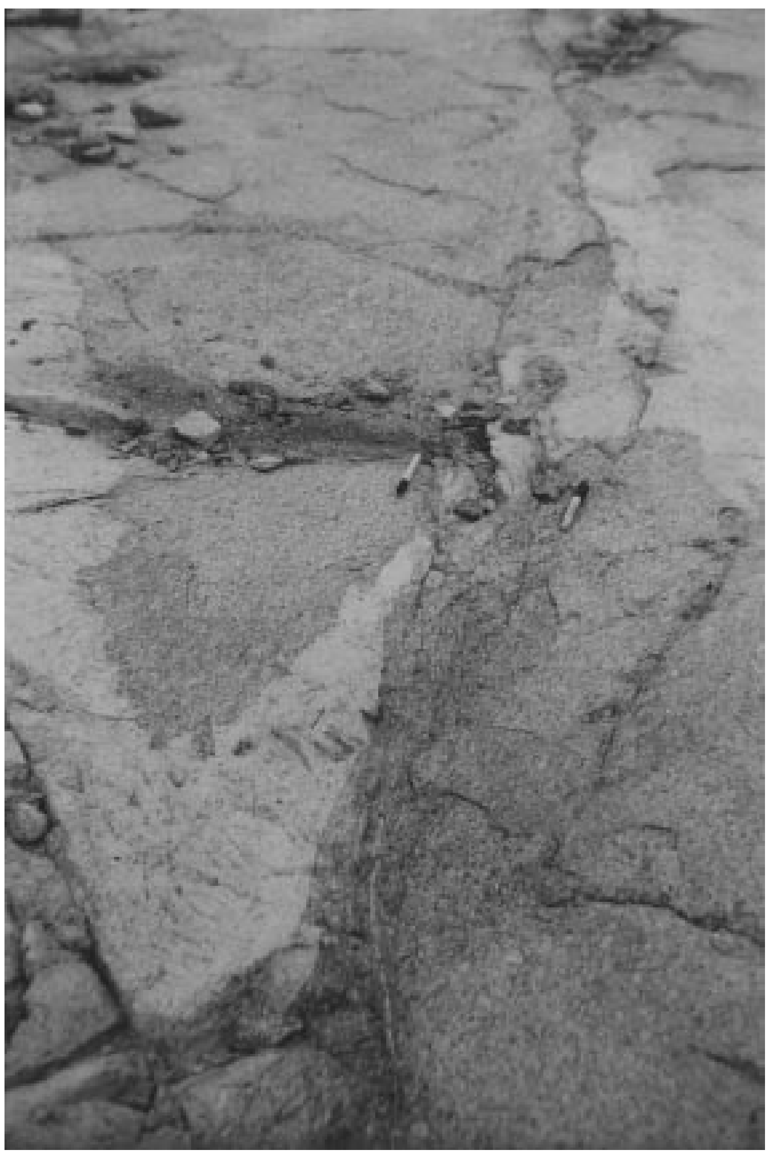

Fig. 2. Sinistral shear zone from within the RFSZ showing ~2 m of offset of an aplite dike (see Fig. 1 for location). The trend of the shear zone extends past the edges of the aplite dike, as noted by the concentration of mafic minerals. There is no evidence that this shear zone initiated on a pre-existing aplite dike. Sinistral shear zone nucleation without aplite dikes typifies deformation in the Mono Creek granite, as well as the Lake Edison and Turret Peak plutons.

Blanquat, 1997), which constrains their age. The age of the dextral shearing is constrained further north, where U/Pb resetting and $^{40}Ar/^{39}Ar$ on biotite at 80–76 Ma is reported from the dextral shear zone within the Tuolumne Intrusive series (Fleck *et al.*, 1996). However, these shear zones are kinematically linked (Greene and Schweickert, 1995; Tikoff and Greene, 1997) and thus are likely to have been active simultaneously. These relations are corroborated further south along the Rosy Finch shear zone. In the Turret Peak pluton, a clear mutual cross-cutting of sinistral (~105°) and dextral shear zones (~000°) is observed (Tikoff, 1994; Tikoff and Saint Blanquat, 1997). Thus, the development of the pervasive dextral shearing and sinistral shearing is broadly synchronous.

5. Christiansen and Pollard (1997) indicate that the sinistral shear zones are primarily restricted to their field area. This is incorrect. Approximately E–W oriented, sinistral shear zones are found throughout the Mono Creek granite, generally associated with the Rosy Finch shear zone. The northernmost occurrence of sinistral shear zones is near Mammoth Lakes in the northern part of the Rosy Finch shear zone (Fig. 1). Similar shear zones are also found further south in the Mono Creek, Lamarck, and Turret Peak plutons, within and adjacent to the Rosy Finch shear zone (Tikoff, 1994; Tikoff and Saint Blanquat, 1997). As noted by Tikoff and Saint Blanquat (1997), the sinistral shearing has a conjugate orientation to the dextral Rosy Finch shear zone. However, we emphasize that the dextral shearing is more pervasive and has significantly more offset than the individual sinistral shear zones (Tikoff and Teyssier, 1994; Greene and Schweickert, 1994; Tikoff and Saint Blanquat, 1997) which typically have less than 20 m offset (Tikoff and Saint Blanquat, 1997; Christiansen and Pollard, 1997). Any model for the genesis of sinistral shear zones must take into account the observation that they are spatially associated with the broad dextral Rosy Finch shear zone.
6. One of the main conclusions of the paper is that the sinistral shear zones occurred because of the presence of pre-existing aplite dikes. This is largely inconsistent with our field observations. Further north in the Mono Creek (e.g. Tully Lake traverse; Tikoff and Teyssier, 1994) there are still sinistral shear zones, but fewer aplitic dikes. At this locality, sinistral shear zones are not initiating on aplite dikes nor are they intruded by the dikes (Fig. 2; see Fig. 1 for location). Our figure shows an aplitic dike which intruded prior to sinistral shearing, and was dragged into parallelism with the sinistral shear zone. The aplite dike is clearly deflected when it contacts the shear zone and is highly deformed within the shear zone. The aplite dike is also oriented at a low angle to the mylonitic, sinistral shear zone, and yet is not highly deformed away from the shear zone. If the mechanism of shear

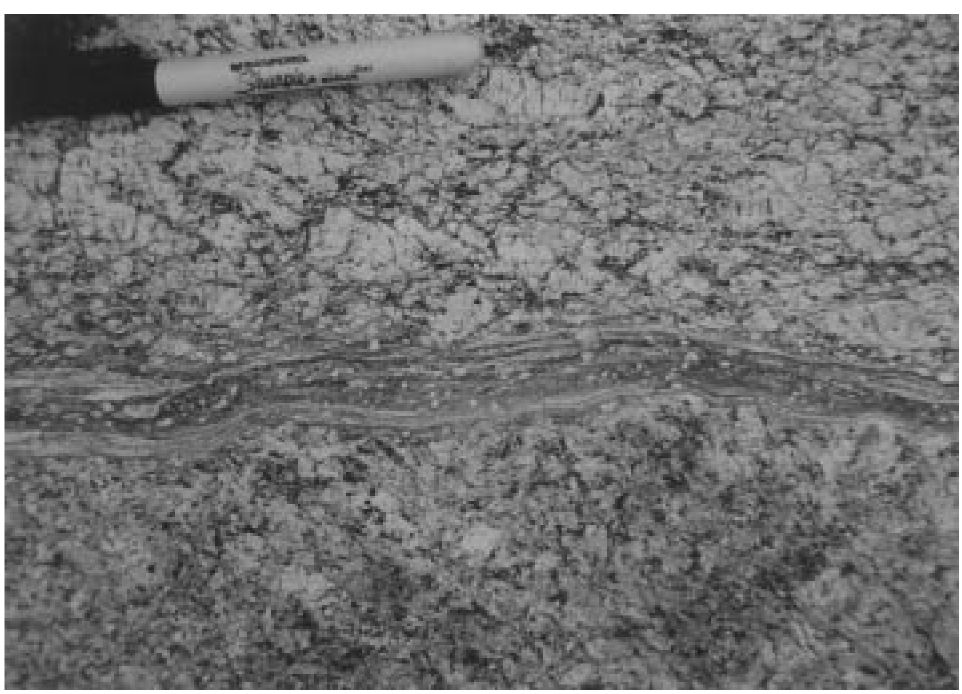

Fig. 3. Grain size reduction in a sinistral shear zone within the RFSZ (see Fig. 1 for location). The progressive grain size reduction and concentration of mafic minerals within the shear zone suggests the zone nucleated in the granite and not on a pre-existing aplitic dike.

zone initiation in aplite dikes played a major role, as proposed by Christiansen and Pollard (1997), one would expect shearing to have concentrated in the dike. The sinistral shear zones are generally hosted in granite, not in aplite dikes, as suggested by progressive grain size reduction (Fig. 3), the mafic character of the mylonites (Figs 2 & 3), and local preservation of large K-feldspar megacrysts within the sinistral shear zones. In the southern Mono Creek granite, small-scale sinistral shear zones are also observed developing in granite (Tikoff, 1994). According to our mapping, the development of sinistral shear zones without aplite dikes is the most general field relationship.

SUMMARY

The main point of the article by Christiansen and Pollard (1997) is that pre-existing dikes concentrated the sinistral shearing. In light of the discussion above, it is clear that the aplite dikes are not generally required for sinistral shearing.

Ignoring the relation of the sinistral shear zones to a larger dextral system, forming a genetically related and conjugate system prevents the authors from addressing the fundamental problem of initiation of the sinistral shear zones. We emphasize that because of the complex heat distribution in a magmatic arc setting and the arc-scale kinematics, coeval submagmatic to low-temperature fabrics may develop synchronously in different parts of the system. However, we are then left with the important question of how the small-scale sinistral shear zones mechanically relate to the larger dextral system. We do not think that the answer lies in the hypothetical rotation of stresses due to local heterogeneities (dikes) identified as potential precursors of shear zones. It is more useful, in our view, to consider other mechanisms of shear zone localization, such as shear instabilities (Hobbs *et al*., 1989; Dutruge *et al*., 1995) developed in the broad framework of regional tectonics.

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