Journal of Structural Geology 50 (2013) 54–81

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

High temperature fracturing and ductile deformation during cooling of a pluton: The Lake Edison granodiorite (Sierra Nevada batholith, California)

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ARTICLE INFO

Article history:
Received 14 January 2012
Received in revised form
28 May 2012
Accepted 4 June 2012
Available online 15 June 2012

Keywords:
Deformation during pluton cooling
Nucleation of ductile shear zones
Joints
Interplay between fracturing and ductile deformation
Sierra Nevada

ABSTRACT

In the Bear Creek area of the Sierra Nevada batholith, California, the high temperature postmagmatic deformation structures of the Lake Edison granodiorite include steeply-dipping orthogneiss foliations, joints, and ductile shear zones that nucleated on joints and leucocratic dykes. Exploitation of segmented joints resulted in sharply bounded, thin shear zones and in large slip gradients near the shear zone tips causing the deformation of the host rock at contractional domains. The orthogneiss foliation intensifies towards the contact with the younger Mono Creek granite and locally defines the dextral Rosy Finch Shear Zone (RFSZ), a major kilometre-wide zone crosscutting the pluton contacts. Joints predominantly strike at N70–90°E over most of the Lake Edison pluton and are exploited as sinistral shear zones, both within and outside the RFSZ. In a narrow (~250 m thick) zone at the contact with the younger Mono Creek granite, within the RFSZ, the Lake Edison granodiorite includes different sets of dextral and sinistral shear zones/joints (the latter corresponding to the set that dominates over the rest of the Lake Edison pluton). These shear zones/joints potentially fit with a composite Y–R–R′ shear fracture pattern associated with the RFSZ, or with a pattern consisting of Y–R-shear fractures and rotated T′ mode I extensional fractures. The mineral assemblage of shear zones, and the microstructure and texture of quartz mylonites indicate that ductile deformation occurred above 500 °C. Joints and ductile shearing alternated and developed coevally. The existing kinematic models do not fully capture the structural complexity of the area or the spatial distribution of the deformation and magmatic structures. Future models should account more completely for the character of ductile and brittle deformation as these plutons were emplaced and cooled.

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1. Introduction

Deformation within all structural levels in the lithosphere is commonly localized along tabular zones such as faults in the upper brittle field and ductile shear zones at deeper and hotter levels. Ductile shear zones have been described in many rocks, including metagranitoid rocks and granitoids. Granitoids are of special relevance since they are considered as representative of the mean composition of the middle continental crust. They represent an ideal research target given their relatively simple mineralogy and, to a first approximation, homogeneous and isotropic structure.

In granitoid plutons emplaced in the upper brittle crust, ductile shear zones can develop during postmagmatic cooling even in shallow intrusions (Gapais, 1989; Pennacchioni, 2005; Pennacchioni et al., 2006; Smith et al., 2011). The pristine structures and fabrics in these ductile shear zones are well preserved and show little sign of subsequent overprinting. The time available for ductile deformation in a cooling pluton is sufficiently short that, in many cases, the accumulated ductile strain is small and the incipient stages of deformation are preserved. Granitoid plutons are therefore particularly valuable for the study of shear zone initiation in the upper crust and could reflect the processes of shear localization in the middle and lower crust.

Rock analogue materials used in lab experiments and idealized materials considered in numerical simulations of the nucleation of ductile shear zones in rocks are typically homogeneous and isotropic with dispersed weak flaws (e.g., Grujic and Mancktelow, 1998; Mancktelow, 2002; Mandal et al., 2004; Misra and Mandal,

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http://dx.doi.org/10.1016/j.jsg.2012.06.001

2007). At the grain scale they compare well with granitic rocks with sparse biotite, scattered within a quartz–feldspar matrix. Using varied material rheologies (including linear to power-law visco-elastic materials) and different bulk deformation styles (ranging from pure to simple shear), lab experiments and models have shown that conjugate shear zones develop, linking weak particles initially aligned with planes of maximum shear stress. Hard-rock creep experiments on granitic rocks, using a solid-medium Griggs apparatus, show that microshear zones initiate by linkage of weak biotite grains (Holyoke and Tullis, 2006), consistent with predictions of rock analogue experiments and numerical models. Field observations, however, consistently indicate that mesoscopic shear zones exploit pre-existing planar structural (e.g., joints) or compositional heterogeneities (e.g., dykes). Shear zones that develop this way seldom, if ever, propagate as in-plane ductile shears or shear fractures beyond the original extent of the heterogeneity (e.g., Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007).

The Mount Abbot quadrangle in central-eastern Sierra Nevada batholith, California (Lockwood and Lydon, 1975), has hosted numerous detailed studies on postmagmatic deformation of granitoids. This reflects, in part, the extent of spectacular exposures in glaciated outcrops. In this area, Segall and Pollard (1983a) and Segall and Simpson (1986) first established that ductile shear zones nucleated on precursor mineralized joints, and Christiansen and Pollard (1997) recognized that ductile shear focused on aplitic dykes. These nucleation modes were later recognized to occur in many other granitic plutons and have been suggested as a general way small-scale ductile shear zones nucleate (Guermani and Pennacchioni, 1998; Pennacchioni, 2005; Mancktelow and Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007).

In spite of the body of research stemming from the Bear Creek area, an overview of the existing extensive literature of brittle and ductile deformation features of this area reveals many outstanding issues (see discussion in Section 2). In addition, although the deformation structures described within this classic area resemble those in other plutons (e.g., the Adamello pluton in Southern Alps: Pennacchioni et al., 2006), remarkable differences exist in the descriptions of the shear zones and the interpretations of their genesis.

This paper presents new data from the Bear Creek area to contribute to a better understanding the deformation history of a cooling pluton, especially with regard to the relative timing and ambient conditions of formation of brittle and ductile deformation structures. In particular, we provide evidence for the development of joints and ductile shear zones under the same high temperature (>500 °C) conditions. This stage of deformation predated cataclastic deformation along the same structural planes at lower temperatures (~250 °C). Detailed structural maps we have prepared of selected glaciated outcrops of the Bear Creek area evidence a heterogeneous distribution of structures not previously reported. Information from the mapped outcrops provides constraints for models of the regional tectonic stress field and/or of the internal thermal stress related to pluton emplacement and cooling.

2. Geological background

2.1. Plutonic rocks

The granitoid plutons within the Mt. Abbot quadrangle belong to Mono Pass Intrusive Suite (Bateman, 1992) of the Sierra Nevada batholith (Fig. 1). The Mono Pass Intrusive Suite together with the Sonora, Tuolumne (to the north) and Mt. Whitney (to the south) Intrusive Suites occur along the eastern margin of the batholith, and represent the last major pulse of Late Cretaceous magmatism in the Sierra Nevada (Fig. 1b). The plutons of the Mono Pass Intrusive Suite are elongated in an NW–SE trend and become progressively younger towards the NE (Fig. 1b). The plutons considered in this study are the Lake Edison granodiorite, *Kle* (Lockwood and Lydon, 1975) (88 ± 1 Ma: Tobisch et al., 1995), and the adjacent younger Mono Creek granite, *Kmc* (Bateman, 1992) (86 Ma: cfr. Tikoff and de Saint Blanquat, 1997).

2.2. Deformation structures

The occurrence of joints and faults in many parts of the Sierra Nevada batholith has been known for many years (e.g., Becker, 1891; Cloos, 1936; Mayo, 1941; Bateman, 1965). However, the interpretation of the nature of joints and small faults is controversial and the ambient conditions under which they formed are not well defined yet.

In a study over a large area of the central Sierra Nevada, Lockwood and Moore (1979) recognized that strike-slip faults with small amounts of slip (less than a few metres) occur ubiquitously, mainly forming two conjugate steeply-dipping sets (usually with one dominant set). These faults are subparallel to joints filled with quartz, epidote and chlorite. They concluded, as did Becker (1891), that the conjugate small faults, and implicitly the subparallel joints, developed under a stress field consistent with the maximum shortening direction bisecting the acute angle between the two sets. They briefly mentioned that, at some places, plastic drag adjacent to small faults suggested that shearing occurred “at considerable depth while the pluton was semiplastic”.

Segall and Pollard (1983a) also described subparallel small faults and mineralized (epidote–chlorite-filled) joints (mode I fractures) in outcrops of the Bear Creek area investigated by Lockwood and Moore (1979). The small faults there the authors reported on display sharp boundaries with the host rock, and sharp offsets of crosscut dykes; they contain a deformed mineral filling of epidote, chlorite and quartz, and a few millimetre thick foliated package, defined by phyllosilicates (embedding rounded feldspar porphyroclasts), and ribbons of dynamically recrystallized quartz. The latter characteristics connote the small faults as ductile shear zones (as explicitly reiterated by Segall and Simpson, 1986). They concluded that small faults exploited older mineralized joints. Reactivation of a joint in shear resulted in the development of extensional wing cracks at the joint tips without in-plane propagation of the fault beyond the original extent of the joint. Segall and Pollard (1983b) specifically focused on the origin of joints in a study based on field observations in the area near Florence Lake; this area is located SE of the Bear Creek area, and the joints are arranged in a single set striking N10–20°E, which is quite different from the N70–90°E strike of the prominent set of sinistral small faults in the Bear Creek area. They observed that many of the studied joints do not show any discernible shear offset even at the microscopic scale (with individual magmatic crystals perfectly matching across the joints). Based on these observations, they concluded that the joints were mode I fractures, refuting the conclusion by Lockwood and Moore (1979) that they originated as conjugate shear fractures.

The reactivation of the joints in shear has been explained by two different models: (i) a clockwise rotation of the joints due to large-scale monocline kink bands (Bear Creek kink fold) under a constant orientation of the maximum horizontal regional stress σ_{Hmax} (Davies and Pollard, 1986; Pachell et al., 2003), and (ii) a counter-clockwise rotation of σ_{Hmax} through time from N70°E (i.e. parallel to the main set of joint in the area) to NNE during shear reactivation (Segall and Pollard, 1983a). Bergbauer and Martel (1999) considered that the stress field during the opening of the joints reflected a regional tectonic contribution as well as a thermal contribution associated with cooling of the host pluton.

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