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Structural Analysis and a Kink Band Model for the Formation of the Gemini Fault Zone, an Exhumed Left-Lateral Strike Slip Fault Zone in the Central Sierra Nevada, California

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STRUCTURAL ANALYSIS AND A KINK BAND MODEL FOR THE FORMATION OF
THE GEMINI FAULT ZONE, AN EXHUMED LEFT-LATERAL
STRIKE SLIP FAULT ZONE IN THE CENTRAL
SIERRA NEVADA, CALIFORNIA

by

Matthew A. Pachell

A thesis submitted in partial fulfillment
of the requirements for the degree
of
MASTERS OF SCIENCE
in
Geology

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UTAH STATE UNIVERSITY
Logan, Utah
2001
ABSTRACT

Structural Analysis and Regional Tectonic Setting of the Gemini Fault Zone, an Exhumed Left-Lateral Strike-Slip Fault Zone in the Central Sierra Nevada, California

by

Matthew A. Pachell, Master of Science
Utah State University, 2001

Major Professor: Dr. James P. Evans
Department: Geology

The structure and regional tectonic setting of an exhumed, 9.3-km long, left-lateral strike-slip fault zone elucidates processes of growth, linkage, and termination for strike-slip fault zones in granitic rocks. The Gemini fault zone is composed of three steeply dipping, southwest-striking, noncoplanar segments that nucleated and grew along preexisting joints. The fault zone has a maximum slip of 131 m and is an example of a segmented, hard-linked fault zone in which geometrical complexities of the faults and compositional variations of protolith and host rock resulted in nonuniform slip orientations, complex interactions at fault segments, and an asymmetric slip-distance profile. Regional structural analysis shows that joints and left-lateral fault zones have accommodated slip within a 4.8-kilometer wide, right-lateral monoclinal kink band with vertical fold axes and northwest-striking axial surfaces. Geometric modeling of the kink band indicates that as little as 1.1 km of right-lateral displacement across the kink band may have produced the observed slip on km-scale faults within the kink band.

(121 pages)
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Matt Pachell
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CHAPTER 1
INTRODUCTION

Fracture and fault identification, characterization, and interpretation are arguably among the most important geologic topics that impact humans today. Earthquakes, oil exploration and production, ore deposition, ground water exploration and remediation, hazardous waste deposition, and urban planning are all greatly influenced by the occurrence of these structures. Because fractures and faults are often poorly exposed, their detailed structure is difficult to constrain. Furthermore, the characteristics of active fracture and fault systems at seismogenic depths are difficult to characterize because data is typically limited to poor resolution geophysical techniques or cores, which provide a one dimensional view of a complex system. Studies of well-exposed fracture and fault systems that have been exhumed from mid-crustal levels can provide insights into the processes of fracture and fault initiation, growth, linkage, and termination at seismogenic depths.

The eastern Sierra Nevada mountains of California are an ideal setting for studies of exhumed fracture and fault systems. Here, glaciated granitic rocks with sparse vegetation provide a excellent opportunity to examine the detailed structure of joints and left-lateral strike-slip fault zones. The Mount Abbot geologic quadrangle (Lockwood and Lydon, 1975) lies at the eastern crest of the Sierra Nevada at elevations of 3220 to 3915 m, where excellent exposures allow detailed investigation over ~700 m of structural relief. The structures exposed in the quadrangle have been exhumed from 8 to11 km (Ague and Brimhall, 1988, their Fig. 7) and were active at the base of the seismogenic zone (Chapter 2 of this thesis). The fault zones cut granitic plutons that are petrographically distinct (Bateman, 1992), but are relatively mechanically homogeneous and overprinted by few post-emplacement deformational events. This makes field-based studies that address fracture and fault initiation, growth, and termination less complicated. Furthermore, field-
based studies of natural fracture and fault systems in granitic rocks can be used to constrain laboratory experiments and models of fracturing and faulting in granite (e.g., Reches and Lockner, 1994; Moore and Lockner, 1995).

Chapter 2 of this thesis presents the results of a structural analysis of the Gemini fault zone. I present the geologic setting, field expression of the fault zone, and data on the geometry of the fault zone, slip-distance profile, slickenline orientations, and microstructural variations along strike. I discuss the scaling similarities and differences between meter- and km-scale left-lateral strike-slip faults in the study region. I then discuss preexisting structures and their influence on fault zone geometry and suggest that the Gemini fault zone formed and grew along preexisting parallel joints that coalesced via complex linkage zones. I discuss the slip-distance profile in terms of segmentation and slip transfer through segment boundary zones. I conclude with a discussion of the lateral distribution of microstructural deformation mechanisms and show that narrow slip surfaces form early in fault-zone development and are operative on segments regardless of their ultimate slip magnitude.

Chapter 3 focuses on part of the eastern Bear Creek kink band and its genetic association to the Gemini fault zone. I quantify the orientations of the kinked joints and faults, provide an estimate of the paleostress direction for the kink band, and determine the magnitudes of north-south, right-lateral displacement across the entire kink band and northeast-southwest, left-lateral slip on individual faults within the kink band. The left-lateral slip estimates are compared with field observations on the Gemini fault zone in order to assess the validity of the geometric model (Chapter 2 of this thesis). Sensitivity analysis examines how sources and magnitudes of error affect the estimated amount of right-lateral kinking and left-lateral slip. I discuss the major structural elements in the Mount Hilgard quadrangle and then propose two tectonic models, constrained by our analyses.
and data from other studies, that may explain the field data and the kinematics of the kink band and left-lateral faults in the quadrangle.

REFERENCES


CHAPTER 2
GROWTH, KINEMATICS, AND INTERNAL STRUCTURE OF AN EXHUMED
10-KILOMETER LONG, LEFT-LATERAL STRIKE-SLIP FAULT
IN GRANITIC ROCKS, CENTRAL SIERRA NEVADA,
CALIFORNIA¹

Abstract

Field-based structural analysis of an exhumed, ~10-km long strike-slip fault zone elucidates processes of growth, linkage, and termination along moderately sized strike-slip fault zones in granitic rocks. The Gemini fault zone is a 9.3-km long, left-lateral fault system that was active at depths of 8 to 11 km within the transpressive Late-Cretaceous Sierran magmatic arc. The fault zone cuts four granitic plutons and is composed of three steeply dipping northeast- and southwest-striking noncoplanar segments that nucleated and grew along preexisting cooling joints. The fault core is bounded by subparallel fault planes that separate highly fractured epidote-, chlorite-, and quartz-breccias from undeformed protolith. The slip profile along the Gemini fault zone shows that the fault zone consists of three 2 to 3-km long segments separated by two “zones” of local slip minima. Slip is highest (131 m) on the western third of the fault zone and tapers to zero at the eastern termination. Slip vectors plunge shallowly west-southwest and show significant variability along strike and across segment boundaries. Four types of microstructures reflect compositional changes in protolith along strike and show that deformation was concentrated on narrow slip surfaces at, or below, greenschist facies conditions. Taken together, we interpret the fault zone to be a segmented, hard-linked fault zone in which geometrical complexities of the faults and compositional variations of protolith and host rock resulted in nonuniform slip orientations, complex fault-segment interactions, and an asymmetric slip-distance profile.
1. Introduction

Field-based structural analyses of exhumed fault zones can be used to constrain seismological models of fault zone structure, composition, and deformational processes. Current questions in earthquake seismology that can be partially addressed by field-based geologic investigations include the following.

(1) Why, in some cases, do segment boundaries retard rupture propagation and enhance it in others (e.g., Wesnousky, 1986; Beroza and Spudich, 1988; Harris and Day, 1993, 1999)?

(2) During an earthquake, slip appears to be concentrated in small "patches" (Wald et al., 1991; Rubin et al., 1999). What effects do lateral changes in fault zone composition have on the distribution of slip patches along a fault zone (e.g., Chiarabba and Amato, 1994)?

(3) What is the relationship between irregular fault geometries and stress variations along a fault zone (e.g., Guatteri and Spudich, 1998)?

(4) How do the resulting stress conditions affect slip vectors (e.g., Spudich et al., 1998)? Is this tied to the lateral composition of the fault zone (e.g., Beroza, 1991; Chiarabba and Amato, 1994; Harris and Day, 1997)?

We address these questions by examining the geometry, linkage, termination, slip, and microstructures from the exhumed Gemini fault zone (Martel, 1990), a 9.3-km long, left-lateral strike-slip fault zone in the east-central Sierra Nevada, California. Our analyses, recorded at various stations with a maximum structural relief of ~700 m, is a detailed three-dimensional investigation of kilometer-scale, strike-slip fault zone geometry, kinematics, and microstructural composition.

There are numerous studies of meter-scale (defined here as referring to the trace length of faults) strike-slip faults (e.g., Lockwood and Moore, 1979; Segall and Pollard,)
1983a; Martel et al., 1988; Martel and Pollard, 1989; Segall et al., 1990; Martel and Boger, 1998; Robeson, 1998; Lim and Evans, submitted) as well as at the several tens to hundreds of kilometers-scale (e.g., Sylvester (1988) and references therein), but few studies address the structure of fault zones with trace lengths of 1 to 10 km. The Gemini fault zone is an exhumed, segmented left-lateral strike-slip fault zone where each segment is 2- to 3-km long and capable of producing \( M_b \) 4 earthquakes. If the entire 9.3-km trace length of the fault zone ruptured it could have produced a \( M_b \) 5 to 6 earthquake (Evans et al., 2000). Despite the seismogenic importance of this fault zone and others with similar trace lengths, there is relatively little detailed structural data for such fault zones.

Studies of strike-slip faults at the centimeter- and meter-scale in the Sierra Nevada show that these relatively simple fault zones may coalesce into larger compound fault zones that are meters to hundreds of meters in length (e.g., Martel, 1990). One logical question that has arisen from these studies pertains to fault scaling. Is it possible to apply the observations of meter-scale faults to faults that have traces lengths of several kilometers? Our data can be directly compared to meter-scale faults in the same region (e.g., Martel et al., 1988; Martel, 1990), thus the faulting process can be considered over a range of scales in a consistent lithology.

The Gemini fault zone cuts glaciated granitoids, which provide exceptional exposure and limited lithologic heterogeneity. The granitoids are petrographically distinct (Bateman, 1992), but are relatively mechanically homogeneous and overprinted by few post-emplacement deformational events. This makes field-based studies that address fundamental aspects of faulting, such as fault initiation, growth, and termination, less complicated. Furthermore, field-based studies of natural fault systems in granitic rocks augment laboratory experiments and models of faulting in granite (e.g., Reches and Lockner, 1994; Moore and Lockner, 1995).
This chapter first describes the geologic setting and field expression of the Gemini fault zone. We provide data about the geometry of the fault zone, the magnitude of slip along the fault trace, and mineral lineations and microstructural variations along strike. We discuss the scaling similarities and differences between m- and 10-km scale fault geometries for left-lateral strike-slip faults in the study region. We then discuss preexisting structures and their influence on the geometry of the fault zone and suggest that the Gemini fault zone formed and grew along preexisting parallel joints that coalesced via complex linkage zones. We show that the kinematics of the fault zone can be explained by the involvement of the fault zone within the right-lateral monoclinal Bear Creek kink band (Davies and Pollard, 1986). Next, we discuss the slip-distance profile in terms of segmentation and slip transfer through segment boundary zones. We conclude with a discussion of the lateral distribution of microstructures and show that narrow slip surfaces form early in the development of the fault zone and are operative on segments regardless of their ultimate slip magnitude.

2. Geologic Setting

The Gemini fault zone is located in the Mount Abbot Quadrangle (Lockwood and Lydon, 1975) of the east-central Sierra Nevada, between Yosemite and Kings Canyon National Parks (Fig. 2-1). The granitoids in this area belong to the John Muir Intrusive Suite, a series of elongate northwest-striking Late Cretaceous plutons that extend southward from Yosemite Valley (Bateman, 1992).

The Gemini fault zone strikes approximately northeast-southwest between Royce Lakes and Three Island Lake in the southwestern quarter of the quadrangle and cuts three plutons (Fig. 2-2). These are, from west to east, the Lamark pluton; the Lake Edison pluton; a dike-like body of quartz monzonite; and the Mono Creek pluton (Lockwood and Lydon, 1975; Fig. 2-2). The plutons become less mafic and decrease in age to the east.
The Lamark pluton is a dark, medium-grained, biotite hornblende granodiorite with large euhedral hornblende prisms, mafic lens-shaped inclusions, and a strong foliation (Lockwood and Lydon, 1975). Coleman et al. (1995) report a 91.9±0.6 Ma (U/Pb) date from zircons within the Lamark granodiorite and Bergbauer and Martel (1999), using $^{40}\text{Ar}/^{39}\text{Ar}$, show that hornblende and biotite from within the pluton are 90.3±0.7 Ma and 80.0±0.2 Ma, respectively. The Lake Edison pluton is a fine- to medium-grained homogeneous biotite hornblende granodiorite with sphene and subhedral mafic minerals (Lockwood and Lydon, 1975). Zircons in the Lake Edison pluton have been dated using U/Pb at 88.0±1 Ma (Tobisch et al., 1995). Hornblende has been dated by Bergbauer and Martel (1999), using $^{40}\text{Ar}/^{39}\text{Ar}$, at 86.5±0.8, 88.7±0.4, and 85.3±0.7 Ma. Biotite from the Lake Edison pluton has been dated using $^{40}\text{Ar}/^{39}\text{Ar}$ at 83.0±0.1, 80.7±2, and 80.6±0.2 Ma (Bergbauer and Martel, 1999). A dike-like body of fine- to medium-grained biotite quartz monzonite and granite exists in the center of the Lake Edison pluton. This body has no official name (Lockwood and Lydon, 1975) and is referred to here by its map symbol, "Kqm1." Near the Gemini fault zone, Kqm1 is several hundred meters wide and ~7-km long. To the east, the Gemini fault zone cuts the Mono Creek pluton. The Mono Creek pluton is a coarse-grained, porphyritic quartz monzonite that contains minor hornblende and sphene (Lockwood and Lydon, 1975). The Mono Creek pluton has been dated at 78.1 to 79.6 Ma using U/Pb, (Evernden and Kistler 1970) and 86 Ma (U/Pb; Tikoff and Saint Blanquat 1997 citing personal communication with B. Carl 1996). The uncertainties associated with these dates are unreported. Bergbauer and Martel (1999) date hornblende and biotite within the Mono Creek pluton to be 84.5±0.6 Ma and 81.1±0.1 Ma, respectively.

Several lines of evidence suggest that the left-lateral strike-slip faults in the study area were active at depths of 8 to 11 km. Amphibole geobarometry shows that crystallization pressures across the Sierra Nevada batholith decrease from west to east (Ague and
In the Mount Abbot quadrangle, crystallization pressures are estimated to be between 2 to 3 kb, or 8 to 11 km (Ague and Brimhall, 1988, their Fig. 7). Segall et al. (1990) dated muscovite from left-lateral strike-slip fault zones near Bear Creek and obtained an age of faulting of 78.9±0.4 Ma (K/Ar and 40Ar/39Ar methods). This age is close to the crystallization age of the Mono Creek pluton. Assuming a geothermal gradient of 30 to 35˚ C / km and the 8 to 11 km depth estimates of Ague and Brimhall (1988), the Gemini fault zone was likely to have been active at or near the base of the seismogenic zone.

Pluton contacts dip steeply and record slip along the fault zone. Along the Gemini fault zone the contact between the Lamark granodiorite and the Lake Edison granodiorite dips steeply and is gradational over 3 to 5 m. In the field it is defined by a 1- to 3-m thick band of north-south elongate mafic inclusions that separate a porphyritic facies of the Lamark granodiorite from a finer-grained, slightly more felsic Lake Edison granodiorite. Although previously mapped as a porphyritic facies of the Lamark granodiorite (Lockwood and Lydon, 1975), we observed no compositional difference between the porphyritic Lamark granodiorite and the non-porphyritic Lamark granodiorite in the field or in thin section. Tikoff and Saint Blanquat (1997) identify the porphyritic facies of the Lamark granodiorite and interpret it to have been emplaced into a weak zone controlled by right-lateral shearing along the Rosy Finch shear zone. The contact of the Lake Edison granodiorite and Kqm1 dips steeply and sharply juxtaposes the dark-colored Lake Edison granodiorite against the lighter Kqm1. Along the Gemini fault zone, the contact of the Lake Edison granodiorite and the Mono Creek pluton is defined by a narrow (20 to 70 cm) band of feldspar crystals that dip steeply and juxtapose the dark-colored Lake Edison granodiorite and the lighter Mono Creek pluton (Fig. 2-3).

The Lamark granodiorite and the Lake Edison granodiorite have a prominent steeply dipping, north-northwest-striking foliation defined by elongate biotite and hornblende.
crystals and elongate mafic inclusions. The Mono Creek pluton, however, exhibits a weakly defined, steeply dipping foliation expressed through biotite and hornblende.

All three plutons are cut by aplite and pegmatite dikes that strike dominantly northwest, northeast, and east. They range in thickness from <10 cm to 200 cm and are up to several hundred meters in length. A series of steeply dipping mafic dikes also cuts the Lamark granodiorite. All three types of dikes were used to measure slip along the Gemini fault zone.

3. Preexisting structures in the study area.

3.1. The Rosy Finch shear zone

The center of the Gemini fault zone crosses subvertical foliation mapped by Lockwood and Lydon (1975) as “a zone of pervasive shearing.” Tikoff (1994) interprets the zone to be part of the Rosy Finch shear zone (RFSZ), a Late Cretaceous right-lateral shear zone thought to be related to transpressional tectonics and pluton emplacement along the axis of the Sierra Nevada batholith. Tikoff (1994) and Tikoff and Greene (1994) classify the RFSZ as part of the Sierra Crest shear zone system, a series of late Cretaceous right-lateral shear zones in the eastern Sierra Nevada (Fig. 2-1). In the study area, the shear zone crosses the Gemini fault zone in the thin neck of the Lake Edison pluton. It is characterized by a broad band of subvertical, northwest-striking mica folia and shallowly plunging lineations defined by elongate quartz grains (Tikoff, 1994; Tikoff and Saint Blanquat, 1997). Dextral sense-of-shear indicators include imbricated porphyroclasts, folded aplite dikes, and displaced feldspar cleavages (Tikoff, 1994). Tikoff (1994) argues that the shear zone is synchronous with the emplacement of the Mono Creek granite and thus the contact with the adjacent Lake Edison granodiorite does not show right-lateral displacement. However, Tikoff and Saint Blanquat (1997) show that the older Lamark granodiorite/Turret Peak granite contact in the West Pinnacles Creek valley, which is ~1.5
km south of the Gemini fault zone, has as much as 1.2 km of right-lateral offset. $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of metamorphic biotite and hornblende from the Rosy Finch shear zone yield ages of $83.7\pm 0.4$ Ma and $87.3\pm 0.2$ Ma, respectively (Tobisch et al., 1995). A possible kinematic relationship between the Rosy Finch shear zone and the Gemini fault zone is discussed below.

3.2. Joints

Numerous studies in the Mount Abbot quadrangle show that joints were reactivated as left-lateral strike-slip fault zones (Lockwood and Moore, 1979; Segall and Pollard, 1983a; Martel et al., 1988; Martel and Pollard, 1989; Segall et al., 1990; Martel and Boger, 1998; Robeson, 1998; Bergbauer and Martel, 1999; Lim and Evans, submitted). These studies illustrate that steeply dipping, northeast-striking joints formed during the waning stage of late Cretaceous magmatism. Segall and Pollard (1983a) show that joints, filled with chlorite, epidote, sericite, muscovite, calcite and possibly some zeolites, strike northeast, dip steeply southeast, and range in length from millimeters to tens of meters. The ages of the plutons (~86 to 91 Ma) and the left-lateral faulting (~79 Ma) closely bracket the age of jointing and suggest the joints opened as the plutons cooled. Bergbauer and Martel (1999), through thermo-elastic modeling of the Lake Edison pluton, demonstrate the importance of pluton geometry on the orientation of the cooling joints. Their model shows that cooling joints would tend to develop orthogonally to the pluton boundary and terminate at, or just outside, the pluton boundaries (Bergbauer and Martel, 1999). Their model suggests that the geometry of the Lake Edison pluton is an influence on joint orientation, except where the anisotropy of the Rosy Finch shear zone influences the joint pattern (Bergbauer and Martel, 1999).

Many of the joints were later reactivated to form left-lateral strike-slip fault zones (Martel et al., 1988) that range in trace length from meters to several kilometers. Individual fault zones link via splay fractures that strike ~30° counterclockwise to the main fault
strand, an orientation that is thought to parallel the maximum compressive stress at the time of faulting (Martel et al., 1988). Martel et al. (1988) show that fault propagation did not result in the generation of new fault-parallel fractures, but was the result of the linkage of individual joints and indicates that the joints control the geometry of the younger faults.

Adjacent to the Gemini fault zone, there are joints and small faults (reactivated joints) that have slickenlines, slickensides, and net slips of ≤ 1 m. Aerial photographs of the study area show that vegetated or snow-bound troughs, spaced ~0.1 to 0.5 km apart, are common. If these troughs contain fault zones, the Gemini fault zone may be one of many km-scale fault zones in the region.

4. Methods

The analyses and interpretation of the geometry and kinematics of the fault zone and joints are based on field observations and mapping on a topographic base and unrectified aerial photographs at a scale of approximately 1:14,000. These data were later transferred to a rectified orthophoto quadrangle at a scale of 1:24,000. Steep cirque headwalls were mapped on aerial photos from selected vantage points. Fault strikes and dips are presented using a right-hand rule. The slip-distance analysis was completed by matching dikes, schlieren bands, or pluton contacts that crossed the fault zone at high angles. Slip was calculated using geometric diagrams and lower hemisphere stereonets, which take into account the apparent dip of the dike, pluton contact, or schlieren bands on the fault surface, slip vectors, and topography. The microstructural observations and interpretations are based on analyses of fifty one 50 mm x 76 mm thin sections cut in two orientations: (1) perpendicular to the fault surface and parallel to slip vector, and (2) perpendicular to both the fault surface and the slip vector.

5. Results
5.1. Geometry and kinematics of meter-scale structures

The sigmoidal trace of the Gemini fault zone in the study area is 9.3-km long, trends northeast, and is composed of a linked series of steeply dipping faults (Fig. 2-2). Commonly the fault is expressed as a snow- or vegetation-filled topographic depression bounded by two parallel faults. We term this depression the fault trough. Typically the fault trough is 2- to 15-m wide and 1- to 15-m deep (Fig. 2-4a and b). Parallel bounding fault surfaces separate highly fractured chlorite breccias in the trough from undeformed protolith. The trough walls are commonly mineralized with chlorite and epidote and preserve slickenline and slickenside surfaces. Within the trough, the rocks are mostly concealed by vegetation or snow; however, where exposed, consist of a highly fractured chlorite breccia (Fig. 2-4c and d).

The following discussion is divided into three sections that correspond to segments along the fault zone. The segments, identified from the slip-distance profile that is discussed below, include, from west to east, the Three Island Lake segment, the Gemini Lake segment, and the Royce Lakes segment (Fig. 2-5).

5.1.1. The Three Island Lake segment

The eastern part of the Three Island Lake segment trace descends west from the summit of Gemini Peak (3915 m) in a 3- to 8-m wide fault trough that changes to a steep ~50-m high, north-facing fault trough wall (Fig. 2-6, Area A). The wall forms the southern fault trough boundary. In this area, the fault generally strikes east-northeast, dips very steeply south-south-southeast, and has a shallowly west-southwest-plunging slip vector (Fig. 2-6). Farther to the southwest (Fig. 2-6, Area B), the fault zone strikes east-northeast, dips very steeply to the south-southeast, and has slickenlines that plunge shallowly to the east-northeast and west-southwest. In this area, another lineament joins the Gemini fault through a series of termination splays oriented ~30˚ counterclockwise (CCW) to the
connecting strand (Fig. 2-6, Area B). Southwest of this union, the fault zone begins to arc to the southwest in a complex network of fractures forming a horse-tail termination structure and a right step (Area C, Fig. 2-6). The horse-tail structure contains three 0.3- to 0.5-km long splays that strike south and southeast. A right step joins the curving horse tail structure to a straight, northeast-striking, southeast-dipping fault that terminates near Three Island Lake (Fig. 2-6). Near the lake, slip along the fault tapers to zero. The right step contains nearly vertical fault planes with slickenlines that shallowly plunge to the west.

5.1.2. The Gemini Lake segment

The Gemini Lake segment is composed of steep northwest-dipping fault surfaces with nearly horizontal slickenlines (Fig. 2-7). The Gemini Lake segment differs from the Three Island Lakes segment in that there is less variability in slickenline plunges. Most vectors shallowly plunge southwest and northeast. An unusual feature of this segment is the bend in the fault zone map trace that occurs at the summit of a mountain informally called "12221 peak" (Fig. 2-7, Area A). Here, the fault zone trace bends 37° to the north. Although some of this bend may be due to topographic effects of the mountain peak and the northwest dip of the fault surface, a similar bend is observed on aerial photos ~0.3 km to the north-northeast (Fig. 2-7, Area B). Less than 500 m to the north of the Gemini Lake segment, a prominent lineation trends parallel to the Gemini fault zone and terminates into it by a series of left-stepping splays which are ~30° CCW relative to the main strand (Fig. 2-7, Area C). We infer that this lineament is a left-lateral strike-slip fault zone and informally call this strand the Seven Gables fault zone (SGFZ). Near Gemini Lake, the splays of the SGFZ termination dip steeply and strike north-northeast (Fig. 2-7). Lineations plunge shallowly to the southwest and northeast (Fig. 2-7). The linkage zone consists of highly fractured, dark brown-green rocks of the Lake Edison granodiorite that are heavily coated with chlorite, epidote, and iron oxides. The main trace of the Gemini fault zone in
this area is marked by a snow-filled trough and a perennially frozen lake, informally termed "Gemini Lake." The fault zone left-laterally displaces the western contact of the Kqm1 body by ~40 m.

5.1.3. The Royce Lakes segment

The Royce Lakes Segment is the eastern most segment of the Gemini Fault zone. The fault planes within this segment strike dominantly southwest, are vertical or dip steeply northwest, and slickenlines are nearly horizontal or plunge slightly west (Fig. 2-8). The Royce Lakes segment is composed of numerous fault strands that range from 50 to 950 m in trace length. From southwest to northeast, they gently change strike from 040˚ to 025˚ (Fig. 2-8). At the ends of some fault strands, left steps connect to adjacent strands via 50- to 300-m long splays oriented 35 to 65˚ counterclockwise (CCW) from the main strands (Fig. 2-8, Point A). In general, the Royce Lakes segment varies from the southwest to the northeast. The southwest part of the segment is characterized by a complex network of subparallel fault strands, whereas the northeast part of the segment is a less complex system of parallel strands that are widely spaced and less connected by splay fractures. East of Royce Lakes, the fault terminates into a snow-filled trough that parallels the regional northeast-southwest-striking joint set (Fig. 2-8, Point B). Here, the slip across the fault zone diminishes to ≤ 1 m, mineralization decreases, and slickenlines are scarce.

In total, the three segments described are marked by parallel to subparallel vegetated or snow-filled troughs. They are bounded by steeply dipping fault planes, coated in chlorite, epidote, and quartz, that record dominantly strike-slip motion.

5.2. Slip-distance analysis

The degree of fault interaction is important for understanding fault growth and linkage (Peacock and Sanderson, 1991; Peacock and Sanderson, 1994; Dawers and Anders, 1995; Gupta and Scholz, 2000). There are two ways of estimating fault interaction:
separation-overlap ratios and displacement-length (D-L) profiles. Separation-overlap ratios, the ratio of the distance between adjacent faults to the amount of adjacent fault overlap, does not reveal much about the state of interaction within the overlap zone (Gupta and Scholz, 2000). Displacement-length profiles are typically shown for normal faults of varying length and displacement. The focus here is on slip-distance analysis (S-D), rather than displacement-length analysis, which compares faults of differing length.

Slip-distance profiles are rare for strike-slip faults because few markers intersect the fault at high angles (Gillespie et al., 1992). We present a slip-distance profile for the left-lateral strike-slip Gemini fault zone that is constrained by 16 offset markers that include steeply dipping aplite dikes, pluton contacts, and schlieren bands. Slip is calculated by determining the true dip of the marker feature on the fault plane and then creating a scaled-map view and cross-sectional diagram of the fault, the offset markers, and the local topography. Net slip is then measured from the scaled cross sectional diagram.

The S-D profile for the Gemini fault zone is irregularly shaped, has four local maxima, and has a maximum slip of 131 m in the western third of the fault zone (Fig. 2-9). This creates a jagged, asymmetric profile that is skewed to the west. The S-D plot shows two regions of local slip minima. These slip minima were used to define the three segments of the fault zone, the Three Island Lake segment, the Gemini Lake segment, and the Royce Lakes segment, with respective surface trace lengths of 3.2, 2.8, and 3.0 km (Fig. 2-9).

The maximum slip occurs on the southwestern third of the fault zone (Three Island Lake segment). Local slip maxima are near the midpoint of the Gemini Lake segment and northeast third of the fault zone (Royce Lakes segment). Although the three segments are nearly equal length, the maximum slip for the Three Island Lake segment is 131 m, nearly 2 to 3 times that for the Gemini Lake and Royce Lakes segments (Fig. 2-9). Interestingly, the local slip maximum is greatest on the segment that cuts the oldest pluton and least in
the segment that is entirely in the youngest pluton, suggesting that faulting might have first begun in the oldest pluton.

5.3. The reactivation of joints as faults

The main arguments for fault reactivation of preexisting joints are as follows.

(1) The joints and faults contain mineral assemblages of epidote, quartz, and chlorite. Within the joints, the assemblages are undeformed, whereas within the faults, the assemblages are deformed (Segall and Pollard, 1983a; Segall and Pollard, 1983b). Robeson (1998), after performing detailed microstructural analyses, also concluded that the minerals within the joints contained no shear fabrics.

(2) The faults are always associated with joints, however not all joints are associated with faults (Segall and Pollard, 1983a).

(3) Joints and faults form under different stress conditions and are not likely to be coeval. The joints open in the direction of the least compressive stress and propagate in the plane normal to the least compressive stress, whereas the faults slip under conditions where the principle stresses are oblique to the fault surface.

(4) Segall and Pollard (1983a, p. 564), after performing detailed field measurements, conclude that the opening displacement across the joints is much larger than the maximum possible tangential component of shear displacement and state, “[The observations presented in this paper] rule out a shear origin for these joints…” Additionally, Martel et al. (1988) show that tail cracks are found only on the faults and not on the joints, indicating that the joints did not form through shear.

All of the above points indicate that the joints are older than the faults, the joints formed as opening mode fractures, and the faults formed through shearing of the joints.
The fundamental conclusion reached by structural geologists working in the area is that the centimeter- and meter-scale faults nucleated along preexisting joints.

We recorded attitudes for joint and fault planes in the Lamark, Lake Edison, and Mono Creek plutons to see whether the Gemini fault zone is composed of faults that share similar orientations to the joints (Fig. 2-10). In the Mono Creek pluton the joints display two dominant strikes of ~135˚ and ~225˚. The faults have one dominant strike of ~225˚ and both joints and faults dip steeply northwest and southeast. In the Lake Edison pluton, the joints and faults have one dominant strike of ~243˚ and dip steeply northwest (Fig. 2-10). The orientations of the joints in the Lamark pluton show more variability when compared to the Mono Creek and Lake Edison plutons (Fig. 2-10). There are three dominant joint strikes of ~252˚, ~285˚, and ~315˚ that dip northwest, north, and northeast, respectively. Faults in the Lamark pluton have two dominant strikes of ~065˚ and ~082˚ and dip steeply southeast and east-southeast.

When comparing the Lake Edison and Mono Creek plutons, the former has a greater number of joint sets (Fig. 2-10). The increased density and number of joints sets could reflect the ages and thermal histories of the plutons (S. J. Martel, 1999, pers comm.). The Mono Creek pluton, which is the youngest of the three plutons has been subjected to thermal stresses involved in its own emplacement and cooling. The older Lake Edison pluton might have had joint sets from its cooling as well as the heating/cooling cycle associated with the emplacement of the Mono Creek pluton. The Lamark pluton, the oldest of the three, may have been subjected to thermal stresses from its emplacement as well as emplacement of the Lake Edison and the Mono Creek plutons, and is thus likely to have higher joint densities and more diverse joint orientations.

5.4. Slickenline distribution
Variations in slip vector orientations over an entire fault zone are traditionally thought to reflect long-term changes of fault behavior or multiple tectonic events (Roberts, 1996; Shipton and Cowie, in press). Recently, however, some workers show that during earthquakes fault zones may exhibit slip vector (rake) changes along strike and at a single location (e.g., Guatteri and Spudich, 1998). For example, the Nojima and Rokko fault systems during the 1995 Kobe earthquake (Bouchon et al., 1998; Spudich et al., 1998) and the San Andreas fault during the 1989 Loma Prieta earthquake (Beroza, 1991) produced curved and cross-cutting slickenlines where the fault surface was exposed.

Guatteri and Spudich (1998) provide a mechanical explanation for these observations through 3D boundary modeling of temporal slickenline orientation variability during earthquake rupture propagation. They conclude that rake variability is characteristic of fault zones which meet two criteria: (1) a low initial shear stress (~10 MPa) on the fault surface (i.e., the shear traction before an earthquake initiates), and (2) spatial variations in the direction of initial stress. Guatteri and Spudich (1998) conclude that, for low stress events, fault zone geometry is the dominant control of rake variability observed along fault surfaces.

Slickenlines of the Gemini fault zone are measured as the acute angle from horizontal and are broken into two broad categories: rakes that fall in the eastern and western stereonet hemispheres. Most slickenlines on the fault plunge to the west and, at any given site, there is significant variability. For example, data from several sites show >40° of rake variability and data from the station located ~5.6 km along the fault zone show ~85° of rake variability (Fig. 2-9). Data points stacked vertically on top of each other indicate more than one orientation at a station. The data show that: (1) 74% of the slickenline data are oriented between horizontal and 30° down from the west; (2) most of the fault is dominated by strike-slip movement; the mean and median orientations are 12° and 16° west with a standard deviation of 19° west, respectively; and (3) there is significant variability in
slickenline orientation across segment boundaries. If the model of Guatteri and Spudich (1998) is correct, it is possible that the slickenline variability observed along the Gemini fault zone resulted from its complex geometry and resulting stress heterogeneities.

5.5. Microstructures

Microstructural analyses provide insight into internal fault-zone deformational processes, material property variations along fault strike, and fault-zone hydrology, rheology, and evolution. These observations can be used to understand and characterize the occurrence of low- and high-seismic velocity zones (LVZs and HVZs), which are areas along a fault that are composed of weak materials undergoing aseismic slip and strong materials that exhibit large, coseismic slip (Chiarabba and Amato, 1994). Current studies in earthquake dynamics and prediction indicate that these areas can be identified from local earthquake tomography, but the exact structure and composition of these areas remain unclear (Chiarabba and Amato, 1994; Hough et al., 1994; Harris and Day, 1997). Qualitative microstructural analysis of an exhumed seismogenic strike-slip fault zone provide detailed descriptions of fault zone composition and material properties along fault strike (i.e., LVZs and HVZs), document the deformation mechanisms active at seismogenic depths, and provide a link between field-based geologic data and seismic analyses.

5.5.1. Mineralogies

Unlike the plutons, the fault zone contains significant amounts of chlorite, epidote, quartz, sericite, and muscovite. These observations are supported by Segall and Pollard (1983a, b) and Robeson (1998), who, working on smaller fault zones ~2 km to the north, noted all of the above minerals and calcite and zeolites. The mineralogy and the microstructures suggest that the fault zone rocks were deformed at lower greenschist facies conditions.
Qualitative descriptions of microstructures and mineral assemblages of 51 thin sections show that three distinct groups of structures/assemblages exist: mylonites, cohesive cataclasites and breccias, and sericite veins and masses.

5.5.2. Mylonites

Mylonite crops out along the center of the fault zone over a lateral distance of ~1.5 km or 16% of the surface trace length (Fig. 2-9). The mylonites extend from the west slope of Gemini peak at an elevation of ~3915 m to the low divide east of Gemini Lake at an elevation of ~3634 m (Fig. 2-9). The mylonites are zones ~1- to 3-m long, often terminate into a brittle fracture over the distance of 1 to 2 m (Fig. 2-11), and appear to be obliterated by the larger brittle faults that comprise the fault core. We use the term brittle fault here to describe epidote and chlorite coated planar fractures that preserve slickenlines. In thin section, the mylonite consists of kink bands of biotite, quartz subgrains, mosaics of fine-grained, serrate grain boundary quartz, and mica and quartz subgrain tails on mantled feldspar and quartz grains (Fig. 2-12a and b). Rotated delta- and phi-type feldspar porphyroclasts, S-C fabrics, and mica fish indicate left-lateral sense of shear (Fig. 2-12a and b). In some sections, the grain size of dynamically recrystallized quartz grains is significantly reduced from ~2 to ≤ 0.15 mm (Fig. 2-12b), indicating prolonged periods of strain at elevated temperatures. The imbricated clasts and bands of mica and dynamically recrystallized quartz define a vertical, east-northeast-striking foliation that roughly parallels the strike of the Gemini fault zone in this area.

5.5.3. Cohesive cataclasites and breccias

The oldest suite of structures to cross cut the ductile structures are fault-parallel bands of cohesive cataclasites and breccias. Following Passchier and Trouw (1996), cohesive cataclasites are defined as having <30% by volume of angular fragments of the wall rock or fractured veins in a fine-grained matrix and cohesive breccias have >30% by volume of
fragments in a fine-grained matrix. The cohesive cataclasites and breccias were observed in samples collected over a lateral distance of 6.8 km or 73% of the fault zone's trace length (Fig. 2-9). They appear to be concentrated in the western half of the fault zone, and become increasingly clast-supported where the texture dies out. The cataclasite and breccia bands range in thickness from ≤ 1 to >50 mm (entire thin-section width) and reach lengths >76 mm (entire thin-section length). In outcrop, some bands are several centimeters thick and extend along the fault for several meters. These textures contain angular clasts of feldspar and dynamically recrystallized quartz that range in size from ≤0.1 to >35 mm and are surrounded by an optically unidentifiable matrix of very fine-grained, dark material that is likely to be oxides and very fine-grained chlorite (Fig. 2-12c). The floating nature of the grains and lack of grain alignment suggests that fluid-assisted deformation (c.f., Chester et al., 1993; Schulz and Evans, 1998) was active during shearing. The cataclasite and breccia bands are cut by sericite veins and areas of sericitization, demonstrating that the formation of the dark oxides, observed in the cataclasite and breccia, predates the sericitized textures described next.

5.5.4. Narrow sericite-filled veins

Transgranular sericite-filled veins are observed nearly the entire length of the fault zone (Fig. 2-9). It is likely that these structures extend farther east to the end of the fault, but limited exposure and steep cirque head walls prevented sampling in those areas. The western termination of the texture approximately corresponds to the end of the fault zone. They occur in a variety of orientations relative to the dominant fault surface. Some veins appear to open along preexisting weaknesses in the material, such as feldspar twinning planes, S-C foliation planes, and grain boundaries, while others seem to cut across grains (Fig. 2-12d). The veins range in thickness from ~0.1 to ~3 mm. Continuous fibers span many vein openings, indicating that the sericite has grown in an opening mode fracture
during static recrystalization (Fig. 2-12e). We observe only one generation of sericite veins in the thin sections.

5.5.5. Wide masses of sericite

The youngest texture, which formed in conjunction with the narrow sericite veins, is masses of sericite crystals. Some masses cover entire thin sections and others occur in distinct veins. The mineralization occurs as a complex patchwork of interlocking grains (Fig. 2-12f). Our thin-section observations suggest that this texture grew, or was sourced from, the narrow sericite veins discussed above and may represent an advanced stage of mineralization. The grains do not show any evidence of deformation, such as bent or folded folia, suggesting that the grains grew via static recrystalization into multigranular voids.

5.5.6. Cross-cutting relationships

Cross-cutting relationships suggest that the microstructures evolved from early ductile to later brittle structures. The mylonites described above are the oldest microstructures observed along the fault zone. They are cut by the cohesive cataclasites and breccias. The cohesive cataclasites and breccias contain angular clasts of dynamically recrystallized quartz and feldspar (Fig. 2-12c). There are no discernable cross-cutting relationships between the cohesive cataclasites and the cohesive breccias. The mylonites and the cohesive cataclasites and breccias are cut by the narrow sericite-filled veins and the wide masses of sericite (Fig. 2-12 d-f), suggesting that the dominant period of mineralization occurred after deformation. The mineralization via the narrow sericite veins and the wide masses of sericite appears to overprint all other microstructures and is observed the entire length of the fault zone.

5.6. Magmatic foliation transects
Microstructures from the Gemini fault zone indicate that, for most of the fault zone’s trace length, slip is concentrated on narrow (<5-cm wide) bands within a 2- to 15-m wide fault trough dominated by brittle deformation processes. To assess the how deformation along the fault zone has been accommodated, we measured attitudes of magmatic foliation in six 30 m transects oriented perpendicular to the fault trough (Fig. 2-13). Areas along strike of the fault zone that experienced distributed strain should exhibit rotation of the magmatic foliation towards the center of the fault zone, reflecting the fault zone’s sense of shear (i.e., deflected foliation into a shear zone; see inset Fig. 2-13). The data for the foliation surrounding the Gemini fault zone show no apparent rotation or drag into the fault zone. This implies that the fault zone has always been deformed in the brittle regime and that all left-lateral strike-slip deformation in confined to the fault trough. The attitude of the foliations measure in the 30-m long transects are consistent with the those recorded by Lockwood and Lydon (1975) farther away from the fault zone. This indicates that, when examined at the map-scale, all deformation associated with the fault zone is confined to the narrow fault trough.

6. Discussion

This paper presents field-based structural analyses of the geometry, kinematics, slip-distribution, and microstructures of a ~10-km long, left-lateral strike-slip fault zone. Next, we evaluate six aspects of the fault zone: (1) fault zone scaling; (2) controls on the geometry of the fault zone; (3) kinematics of the fault zone; (4) the slip-distance profile; (5) slickenline orientation; and (6) lateral composition of the fault zone.

6.1. Fault scaling

Describing the Gemini fault zone using a fault architecture scheme (Chester and Logan, 1986; Caine et al., 1996), we observe that the Gemini fault zone is composed of a highly brecciated and mineralized fault core that is in sharp contact with undeformed
protolith. The core, ~2- to 15-m wide, is bounded by mineral coated, polished, and striated fault surfaces. Little to no damage zone is observed. The fault zone consists of three 2-to 3-km long segments.

Martel et al. (1988) describe left-lateral strike-slip faults in the study region with slip of centimeters to several meters. They describe these "simple fault zones" as having a central zone of highly mineralized breccia and sharp bounding faults that separate the highly fractured core from the relatively undeformed protolith (e.g., Martel et al., 1988). Martel (1990) concludes that the Gemini fault zone grew as splay fractures linked simple fault zones. Our analysis of the internal structure of the Gemini fault zone and the analysis of Martel (1990) suggests that the architecture of the left-lateral strike-slip faults in this area may be scale invariant.

Examples of fault linkage can be seen at two locations along the Gemini fault zone (Fig. 2-14). The left-stepping termination of the Seven Gables fault zone (SGFZ) into the Gemini fault zone (Fig. 2-14, box A) is an example of a km-scale analogue of the meter-scale linkage described by Martel (1990; Fig. 2-15). The geometry and kinematics of this linkage zone are consistent with the meter-scale simple and compound fault zone models of Martel et al. (1988) and Martel (1990). Another example of this type of structure is observed on the Three Island Lake segment. Here, a series of left-stepping lineaments connect two northeast-striking lineaments to the southwest-curving Gemini fault zone (Fig. 2-14, box B). The left-stepping lineaments are oriented ~30° CCW from the northeast-striking lineaments and appear to terminate at the Gemini fault zone.

Martel (1990) classifies the Gemini fault zone as a "compound fault zone", a complex fault system that is composed of "simple fault zones" (Martel et al., 1988; Fig. 2-15). Although the outcrop-scale structure of the Gemini fault zone seems to scale from the "simple faults zones" of Martel et al. (1988; see Martel [1990] for details), when examined at the 10-km scale there are aspects that clearly do not scale from the smaller faults.
(1) The general geometry of the fault zones are drastically different. The ~10-km long Gemini fault zone has a sigmoidal map pattern while most of the fault zones of Martel et al. (1988) and Martel (1990) have, for the most part, relatively straight map traces.

(2) Martel (1990) shows that simple fault zones link via splay fractures to form compound fault zones (Fig. 2-15). The ratio of the simple fault-zone width to the length of the splay fractures is ~9:1 (Fig. 2-15). If adjacent compound fault zones link in a similar manner and if they scale proportionally, one would expect the ratio of fault-zone width to splay length to be similar. Examining the two areas where km-scale splay fractures link the Gemini fault zone to adjacent fault zones (box A and B, Fig. 2-14), a conservative estimate of the ratios of fault-zone thickness to splay-fracture length are much higher, ~25:1. In these two areas, the fault zone is a ~20-m wide and the splay fractures that link the adjacent fault zone to the Gemini are, on average, ~500-m long. This indicates that, when examined at the 10-km-scale, geometries produced through fault zone linkage may not scale proportionally with the m-scale, left-lateral strike-slip fault zones.

(3) Our data show that the western termination of the fault zone resembles the structure described in Grannier (1985) than the splay-fracture terminations described by Martel et al. (1988), Martel (1990), and Segall and Pollard (1983b). The main structure mapped at the western end of the fault zone makes a broad arc to the southwest. Emanating from the main fault strand are a series of southeast-striking splays. The curved nature of the main fault trace suggests that the fault encountered an increased resistance to slip caused by the lack of favorably oriented linkage structures as described for modeled faults by Martel (1999).

6.2. Controls of fault zone geometry
Process zones, areas of enhanced deformation at fault tips, are thought to scale with slip (Cowie and Scholz, 1992). As faults grow, inactivated process zones should be evident in the rock mass surrounding the fault. We do not observe a systematic increase in fracturing from the center of the fault trace towards its ends that might reflect the migration of a process zone and conclude that the fault did not propagate as a planar shear fracture. The fault seems to have grown instead by slip along the preexisting fractures and by their linkage (e.g., Segall and Pollard, 1983b).

The western termination of the Gemini fault zone is a curving horsetail structure. Here, the Lamark pluton has multiple joint sets of varying orientation and thus, the processes of fault-zone termination were different than those acting at the eastern end.

Elastic modeling by Martel (1999) indicates that curving fault ends may develop if the resistance to slip increases significantly near the end of the fault. We hypothesize that the western termination of the Gemini fault zone may be a manifestation of these theoretical solutions. Examining the Gemini fault zone S-D data, the western third of the fault zone has accumulated most of the slip and has a steep (0.18) slip gradient on its western end (Fig. 2-9). Aerial photo analysis and field measurements (Figs. 2-6 and 2-10) indicate that the Lamark pluton, found at the fault zone’s western end, may have multiple joint sets. As discussed above, this may have been the result of the complex thermal history of the pluton. The lack of suitable linkage structures or parallel joints sets may have caused an increased resistance to slip that could have resulted in the curved nature of the western termination of the Gemini fault zone.

6.3. Kinematics

The left-lateral strike-slip kinematics of the Gemini fault zone can be explained by examining the relationship between the joints and the Bear Creek kink band (Davies and Pollard, 1986). The Bear Creek kink band is a 4.8-km wide, 5-km long, right-lateral
monoclinal kink band with vertical fold axes and northwest-striking axial traces in the southeast quarter of the Mount Abbot geologic quadrangle (Lockwood and Lydon, 1975). Here joints and left-lateral faults created a strong anisotropy within an otherwise relatively homogeneous granitoid and enabled the formation of a km-scale kink band. We propose that the right-lateral kinking of the joints formed left-lateral strike-slip fault zones that had trace lengths of several meters to tens of meters (e.g., Martel et al., 1988). Some of these faults coalesced into larger fault zones with trace lengths of ~10 kilometers. This subject is discussed in detail in Chapter 3 of this thesis.

6.4. Slip-distance analysis

Two important points that arise from the slip profile (Fig. 2-9) include evidence for physical linkage (“hard linkage” Walsh and Watterson, 1991) of the fault zone at the segment boundaries and insights into how the fault grew based on current fault growth models. Each point is discussed below.

6.4.1. Linkage structures at segment boundaries

Two zones bound segments along the Gemini fault zone (Figs. 2-9 and 2-16). The western zone occurs at Gemini Lake where the Three Island Lake and Gemini Lake segments converge (Fig. 2-16, box A). No steps or jogs in the fault zone are discernable at this point and linkage of the fault zone to other fault zones via splays is not apparent. We suggest and discuss below that the slip deficit in this region may be explained by the intersection of the Seven Gables fault zone with the Gemini fault zone, which resulted in an area of apparent slip deficit or the interaction of the Gemini fault zone and the northeast-southwest-striking splay fault that intersects the Gemini in this area.

The SGFZ terminates into the Gemini fault zone near Gemini Lake in a series of left-stepping splays (Fig. 2-16, box A, near point A). It is possible that the slip from the SGFZ
was transferred to the Gemini fault zone along the westernmost splay. The sharing of slip between the Gemini Lake segment and the SGFZ would cause an apparent deficit on the Gemini Lake segment (Fig. 2-9). As an alternative hypothesis, the slip deficit may be the result of the mechanical interaction between the Gemini fault zone and the north-northeast-striking fault that intersects the Gemini fault zone at a high angle from the south, west of Gemini Lake (Fig. 2-16, box A, point B). It is possible that some of the slip was transferred to this fault, resulting in a slip deficit in this area.

The eastern segment boundary (the Gemini Lake and Royce Lakes segment boundary) roughly corresponds to the subtle change in joint orientations that is observed ~500 to 700 m east of the Mono Creek and Lake Edison pluton contacts (Fig. 2-16, box B). A slip deficit occurs in the area where the two joint sets overlap. In this area, faults and joints have a wide range of orientations, some traces are curved, and others are at high angles to the main fault-zone trace. We hypothesize that the slip deficit observed along the Gemini in this area may be the result of slip being accommodated by these subsidiary structures.

6.4.2. Fault zone growth

The slip profile is characterized by three local maxima and a steep slip gradient of ~0.18 at the western end of the fault zone. This gradient falls within the ranges of other published slip data of 0.002 to 0.25 as compiled by Shipton (1999) and Shipton and Cowie (in press). Steep slip gradients have been interpreted to indicate fault linkage (Peacock and Sanderson, 1991; Peacock and Sanderson, 1994; Willemse et al., 1996; Gupta and Scholz, 2000) or regions of high yield stress at the fault tip (Martel, 1999). In these models, steep slip gradients occur on the two neighboring ends of adjacent segments. Our data show the highest gradients on the western end of the Three Island Lake segment where there is no other visible interacting fault zone. The asymmetric slip profile observed
on the Gemini fault zone might reflect the lack of suitable linkage structures in the Lamark pluton rather than the mechanical interaction with another fault zone.

Gupta and Scholz (2000), using slip data from small normal faults and an elastic boundary element model, show that the local slip minima at a point of linkage becomes less apparent as the linked fault zone matures. They show that as a fault zone reaches an advanced stage of interaction, the slip profile resembles that of a continuous fault surface (e.g., Cowie and Scholz, 1992). If the model of Gupta and Scholz (2000) is correct and applicable to strike-slip fault zones, the presence of three local slip maxima and the asymmetry of the cumulative slip profile suggests that the Gemini fault zone did not have complete slip transfer through the segment boundaries and was not acting as one continuous fault.

This topic is important for understanding why some segment boundaries efficiently transfer slip of propagating earthquake ruptures and others arrest slip. Here, we have a segmented ~10-km long, left-lateral strike-slip fault that shows apparent segmentation at two locales along its trace. As discussed above, the western segment boundary may not necessarily be a true segment boundary, but might reflect the junction of two fault zones, the Gemini and Seven Gables fault zones, that have created an apparent slip deficit. The eastern segment boundary, however, may be a segment boundary that has formed from the interaction of two joint sets of differing strike. In this area, we see that the segment boundary zone is composed of numerous smaller fault zones that curve or are at high angles to the main fault-zone trace.

Highly fractured and chaotic segment boundaries have been inferred at depth along seismogenic fault zones. It is currently unclear how and why slip is transferred through these zones. Felzer and Beroza (1999), for example, describe segment boundaries for the Emerson fault and the Homestead Valley fault, components of the 1992 Landers earthquake, as areas of structural complexity characterized by off-fault aftershock focal
mechanisms. The eastern segment boundary of the Gemini fault zone appears to be an exhumed analog to the complex structures described by Felzer and Beroza (1999). Such a structure could produce focal mechanisms that do not lie upon the main fault trace.

6.5. Slickenline distribution

Our slickenline distribution data, taken in entirety, are inconsistent with the single-fault slip vector model of Roberts (1996), which shows systematic slickenline changes at segment boundaries (i.e., slip should become progressively steeper away from the center of an elliptical fault). Our data do not fit this model and may be explained four ways.

1. The variable slickenline orientations may reflect stress perturbation during rupture (dynamic stresses). If this is correct, this would suggest that the ruptures that occurred along the Gemini may have been similar to the low initial shear stress and nonuniform stress directions described by Guatteri and Spudich (1998) and discussed above.

2. The range of slickenline orientation may be due to compositional variations along the fault zone.

3. The data may reflect different slip orientations at different times during the fault zone’s history.

4. Roberts’ (1996) model does not apply to ~10-km long strike-slip faults.

6.6. Lateral composition of the fault zone

The distribution of mylonitic textures broadly corresponds to the intersection of the Gemini fault zone and the Rosy Finch shear zone (Fig. 2-9). Other workers in the region (e.g., Martel et al., 1990) observe mylonitic fabrics in ductile structures that are associated with meter-scale brittle faults. They conclude that the occurrence of the ductile structures increases towards the Lake Edison pluton/Mono Creek pluton contact and the ductile fault zones formed shortly after the emplacement of the Mono Creek pluton when the rock was
near the brittle/ductile transition. These ductile structures are essentially the same as those observed along the Gemini fault zone. In the Gemini area, we observed ductile structures as far east as the Lake Edison granodiorite/Mono Creek granite contact (this locale was not along the Gemini fault zone) and as far west as the Lamark granodiorite/Lake Edison granodiorite contact (Fig. 2-9). The occurrence of the ductile structures along the Gemini fault zone better corresponds to the intersection with the Rosy Finch shear zone rather than the Lake Edison granodiorite/Mono Creek granite contact, however, we cannot exclude the possibility of the latter.

We attribute the occurrence of the cohesive breccias and cataclasites to largely reflect protolith mineralogies. The Lake Edison and the Lamark plutons contain a higher density of mafic minerals than the Mono Creek pluton. The mafic nature of the host rock may account for the occurrence of the dark oxide-chlorite matrix in the cohesive cataclasites and breccias.

Recent work on fault zone microstructures suggests that discrete slip surfaces form early in the fault zone’s development and those processes remain operative as the fault zone grows (Evans et al., 2000). These conclusions apply to faults in granite (Lim, 1998; Robeson, 1998), faults in sandstone (Shipton and Cowie, in press), and faults in mixed lithologies (Chester et al., 1993; Chester and Chester, 1998; Schulz and Evans, 2000). The distribution of microstructural textures and inferred processes along the Gemini fault zone indicate the following.

(1) The same deformation mechanisms were active on all segments regardless of their amount of slip. We observe cohesive breccias and cataclasites on segments with >100 m of slip (Three Island Lake segment) and on segments with as little as ~35 m (Royce Lakes segment).

(2) The internal structure of the fault zone is characterized by sharp moduli contrast with the adjacent protolith, which makes the zones very effective reflectors
or traps for internal headwaves and wave reflections (e.g., Ben-Zion and Andrews, 1998).

(3) Microstructures evolve with changing conditions. The transition from high temperature mylonites or cohesive cataclasites and breccias to brittle cracking and sericite veining may reflect increased strain rates (e.g. Martel et al., 1988) or lower temperatures. The well-developed grains of sericite crystals, the youngest microstructure, observed along ~80% of the fault zone suggest that small cracks along the fault zone experienced periods of opening in the brittle regime. These observations imply that the fault zone had transient patches of fault material, perhaps low velocity zones that became high velocity zones, whose physical properties changed through time as the area cooled.

(4) The degree of mineralization observed inside the fault core, when compared to the protolith, suggests that the fault zone acted as a conduit for focused fluid flow (e.g., Chester and Evans, 1993).

7. Conclusions

Our data show that the Gemini left-lateral strike-slip fault zone is composed of numerous steeply dipping, northeast- and southwest-striking fault planes that have mineral lineations that plunge gently to the southwest. The geometry and slip profile of the exhumed fault zone and surrounding lineaments examined here suggest that the fault zone grew from smaller, 2.5- to 3-km long fault segments. The segments became linked through highly fractured zones and left-stepping splays to form a ~10-km long fault zone. Joints and the fault zone have similar orientations and indicate that the fault zone geometry is controlled by the occurrence of preexisting joint sets. The slip-distance data show that the steepest slip gradient occurs at the western third of the fault zone and slip tapers to zero near the fault zone’s eastern and western terminations. Slickenline orientations vary
nonsystematically over the entire fault zone and segment boundaries. We have identified four microstructures that include mylonites, cohesive cataclasites and breccias, and two forms of sericitization, and represent deformation through lower greenschist facies conditions on narrow, brecciated slip surfaces. The distribution of the deformation mechanisms on all segments of varying slip magnitudes implies that the same deformation processes were active at slip magnitudes greater than 35 m. The extensive nature of the sericitization suggests that the fault zone was hydraulically connected during mineralization.

References


Tikoff, B., Blanquat, M. S., 1997. Transpressional shearing and strike-slip partitioning in
the Late Cretaceous Sierra Nevada magmatic arc, California. Tectonics 16, 442-459.


Fig. 2-1. Location of study area. The study area is in the Mount Abbot quadrangle (Lockwood and Lydon, 1975), between Kings Canyon and Yosemite national parks, California, USA. The location of the Sierra Crest shear zone system is taken from Greene and Schweickert (1995)
Fig. 2-2. Geologic map of study area. The Gemini fault zone crosses the Lamark pluton (west), Lake Edison pluton (center), which contains a dike-like body of quartz monzonite (Kqm1, center), and the Mono Creek (east) plutons. The plutons become younger and more felsic to the east. Map modified from Lockwood and Lydon (1975) and Tikoff and Saint Blanquat (1997).
Fig. 2-3. Lake Edison (Kle) and Mono Creek (Kmr) pluton contact. The contact is defined by a nearly vertical band of feldspar megacrysts. View is to the north along the Gemini fault zone, east of 12221 Peak. The length of the scale card is 16.5 cm.
Fig. 2-4. Field photographs of the Gemini fault zone. (a) Photograph of the snow-filled topographic depression (left of the prominent peak) that defines the Gemini fault zone. View is to the northeast from the shoulder of 12221’ Peak. (b) Photograph of the snow-filled Gemini fault trough (linear snow patch in background) crossing through Royce Lakes in the foreground. View is to the west. (c) Photograph of highly brecciated fault core (around geologist's foot) separated from undeformed protolith (upper right) by bounding fault (above scale card). Scale card is 16.5 cm in length. (d) Close up photograph of chlorite breccias within the Gemini fault core. Length of pen is 13.5 cm. Views of (c) and (d) are to the south along the Royce Lakes segment of the Gemini fault zone.
Figure 4. (a) Photograph of highly brecciated fault core (around geologist’s foot) separated from undeformed protolith (upper right) by bounding fault (above scale card). Scale card is 16.5 cm in length. (b) Close up photograph of chlorite breccias within the Gemini fault core. Length of pen is 13.5 cm. Both views are to the south along the Royce Lakes segment of the Gemini fault zone.
Fig. 2-5. Aerial photograph (a) and prominent lineations (b) of field area. Segment boundary zones defined by slip minima on distance-displacement plot (Figure 9). Kl = Lamark granodiorite; Kle = Lake Edison granodiorite; Kqm1 = quartz monzonite/granite (Lockwood and Lydon, 1975).
Fig. 2-6. Map view of the western segment of the Gemini fault zone, the Three Island Lake segment. Stereonets are lower hemisphere, equal area projections of poles to fault planes, slickenlines, mean fault plane (great circle), and mean slickenline (diamond). Upper left stereonet does not have mean slip vector because the data is too scattered to give meaningful results. Kl = Lamark granodiorite; Klp = porphyritic Lamark granodiorite; Klef = fine-grained facies of the Lake Edison granodiorite; Kle = Lake Edison granodiorite; (Lockwood and Lydon, 1975).
Fig. 2-7. Map view of the central segment of the Gemini fault zone, the Gemini Lake segment. Stereonets are lower hemisphere, equal area projections of poles to fault planes, slickenlines, mean fault plane (great circle), and mean slickenline (diamond). Kl = Lamark granodiorite; Kle = Lake Edison granodiorite; Kqm1 = quartz monzonite / granite (Lockwood and Lydon, 1975).
Fig. 2-8. Map view of the eastern segment of the Gemini fault zone, the Royce Lakes segment. Stereonets are lower hemisphere, equal area projections of poles to fault planes, slickenlines, mean fault plane (great circle), and mean slickenline (diamond). Kle = Lake Edison granodiorite; Kqm1 = quartz monzonite / granite (Lockwood and Lydon, 1975).
Fig. 2-9. East-west cross section of the Gemini fault zone. Section shows topography (V.E. = 1.6), lithologies, the Rosy Finch shear zone (after Tikoff and Saint Blanquat, 1997), displacement-distance profile with segment boundaries, microstructural distribution, and slickenline orientation. White areas within the microstructures section represent regions that contain slipped epidote-coated joints.
<table>
<thead>
<tr>
<th>Lamark granodiorite</th>
<th>Lake Edison granodiorite</th>
<th>Mono Creek quartz monzonite</th>
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<tbody>
<tr>
<td><strong>Strike Only</strong></td>
<td><strong>Strike Only</strong></td>
<td><strong>Strike Only</strong></td>
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<tr>
<td>Joints</td>
<td>Joints</td>
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<tr>
<td><strong>N = 200</strong></td>
<td><strong>N = 200</strong></td>
<td><strong>N = 100</strong></td>
</tr>
<tr>
<td>Circle = 8 %</td>
<td>Circle = 12 %</td>
<td>Circle = 16 %</td>
</tr>
<tr>
<td>N = 49</td>
<td>N = 40</td>
<td>N = 35</td>
</tr>
<tr>
<td><strong>Strike and Dip</strong></td>
<td><strong>Strike and Dip</strong></td>
<td><strong>Strike and Dip</strong></td>
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<td>(Kamb Contoured Poles)</td>
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<td>N = 200</td>
<td>N = 49</td>
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</table>

Fig. 2-10. Joint and fault comparison. Rose diagrams of joint and fault plane strikes and lower hemisphere equal area stereoplots of Kamb contoured poles to joints and faults in the Lamark granodiorite (left), Lake Edison granodiorite (center), and the Mono Creek quartz monzonite (right). The data show that the faults have similar orientations, in map view and in 3 dimensions, as the joints.
Fig. 2-11. Photograph of mylonite described in text. The foliation is left-laterally deflected in the shear zone. Photograph is taken near Gemini Lake. Length of pen is 15 cm.
Fig. 2-12. Photomicrographs of the Gemini fault zone microstructures and mineralization. All views are with cross polarized light. (a) Rotated s-type core-mantle porphyroclast showing left-lateral sense of shear. View is oriented parallel to the fault strike. (b) Bands of dynamically recrystallized quartz and feldspar showing a weakly developed S-C fabric. View is oriented perpendicular to the fault plane and parallel to the slip vector. (c) Cohesive breccia with a dark oxide matrix and clasts of dynamically recrystallized quartz. Sericite-filled vein cuts fine grained-matrix and clasts, indicating late-stage vein filling. View is oriented perpendicular to the fault plane and perpendicular to the slip vector. (d) Brittle fracturing and sericite vein filling. Some veins form along preexisting weaknesses in the material, such as feldspar twinning planes, S-C foliation planes, and grain boundaries, whereas others seem to cut across grains without preference. The veins range in thickness from ~ 0.1 to 1.0 mm. View is oriented perpendicular to the fault plane and parallel to the slip vector. (e) Well developed sericite fibers. Vein cuts fine-grained matrix and clasts, indicating growth into an open fracture under static conditions. View is oriented perpendicular to the fault plane and parallel to the slip vector. (f) Well developed sericite crystals. The large size of these crystals suggests that there was a prolonged period of static recrystalization. View is oriented perpendicular to the fault plane and perpendicular to the slip vector.
Fig. 2-13. Strike of foliation versus distance from fault zone. Magmatic foliation was measured at six locations (starred on inset location map) along the Gemini fault zone to determine if the Gemini fault zone deformation was distributed across area wider than the fault trough. If this were the case, the magmatic foliation should be deflected into the fault zone (see inset figure). The lack of any apparent deflection indicates that the deformation along the fault zone was concentrated in the fault trough under brittle conditions.
Fig. 2-14. Examples of splay faults that link adjacent fault zones to the Gemini fault zone. These structures resemble analogous meter-scale structures documented by Martel et al. (1988) and Martel (1990).
Deactivated small fault
Linkage Splay fracture
Simple fault zone
Small fault
Compound fault zone

Fig. 2-15. Progression of meso-scale fault development (modified from Martel, 1990, Fig. 2d). Small faults develop into simple fault zones, which become compound fault zones with increasing slip. Structures, such as fault linkages and terminations are observed at the map-scale in the Gemini area, however the width of the compound fault zone and linkage fractures do not scale proportionately.
Fig. 2-16. Close up of segment boundary zones. The occurrence of Three Island Lake / Gemini Lake segment boundary (box A) may be the result of: (1) the Seven Gables fault zone terminating into the Gemini fault zone, creating an apparent slip deficit near Gemini Lake (box A, point A), or (2) the NNE-SSW striking fault that intersects the Gemini fault zone from the south (box A, point B). We hypothesize that slip may have been transferred to this subsidiary fault zone, resulting in the displacement minima at this locale. The Gemini / Royce Lakes segment boundary may be the result of the increased density of subsidiary faults in this area. The area coincides with a subtle change in joint orientations from NE-SW (box B, point A) to NNE-SSW (box B, point B). It is likely that the slip deficit recorded along the Gemini fault zone in this area is the result of the subsidiary faults accommodating some of the slip.
CHAPTER 3

A KILOMETER-SCALE KINK BAND IN GRANITIC ROCK AND THE FORMATION OF LEFT-LATERAL STRIKE-SLIP FAULTS IN THE CENTRAL SIERRA NEVADA, CALIFORNIA¹

Abstract

Lineament and structural analyses in the north half of the Mount Hilgard 7.5 minute quadrangle, central Sierra Nevada, California indicate that the lineaments represent traces of joints and faults, which have accommodated slip within a 4.8-km wide right-lateral monoclinal kink band with vertical fold axes and north-northwest striking axial planes. The kink band is the mechanism by which the left-lateral strike-slip faults formed throughout the study area. The kink band is unique because it is a kilometer-scale kink band formed in granitic rocks with a mechanical anisotropy formed by closely spaced, mineralized joints and faults. Joints and faults strike ~070˚ within the kink band and 020˚ to 030˚ outside the kink band. Paleostress analyses of the kilometer-scale kink band and other meter-scale kink bands in the study area suggest that the maximum horizontal compressive stress was oriented northeast during kink band formation. Models of the simplified map traces of the kink bands describe the magnitude of right-lateral displacement across the kink band and left-lateral slip on the faults within the kink band. The model, based upon a monoclinal kink band with fixed hinges, does not allow dilation or contraction within the kink band. The results from the geometric modeling indicate that ~3.7 km of right-lateral displacement across the kink band creates 148 m of left-lateral slip on faults within the kink band. The Gemini fault zone, a representative ~10-km long, left-lateral strike-slip fault within the kink band provides slip data to calibrate the model.

¹ Coauthored by Matthew A. Pachell and James P. Evans
We test the model’s sensitivity to four measurement errors: the angle made by the inner and outer limbs of the kink band, the number of faults within the part of the kink band that was studied, and the kink band width and length. The sensitivity analyses indicate that, when the widest margin of errors are incorporated (varying angle of internal angle by 30°, varying the number of slip surfaces from 6 to 37, varying the kink width from 4500 to 6250 m, and varying the kink length from 5000 to 6120 m), the model calculations are geologically reasonable order of magnitude estimates for right-lateral displacement across the kink band (1.6 to 5.6 km) and left-lateral slip on faults within the kink band (47 to 951 m). The geometric model, when constrained by the paleomagnetic data of Ross (1988), estimates that the right-lateral displacement across the kink band to be ~1.1 km and the left-lateral slip on faults within the kink band to be 45 m. These results agree with the 44 m of average slip observed on the Gemini fault zone and suggests that the joints and left-lateral strike-slip faults may have had a curved map pattern. The occurrence of curved lineaments in the southern Sierra Nevada indicate that km-scale kink bands may exist elsewhere in the Sierra Nevada batholith. It is possible that km-scale kink bands, such as the one described here, may represent a process by which late-stage, arc-parallel deformation may be accommodated within transpressional convergent margins.

Introduction

The small, left-lateral strike-slip faults observed within the Mount Abbot 15’ quadrangle, central Sierra Nevada, California are arguably the most intensely studied, meter-scale2, strike-slip faults in the world. Outcrops of glaciated granitic rock with sparse vegetation provide a unique opportunity to examine the detailed structure of these fault zones. Many papers, dissertations, and theses have examined various aspects of the faults (Appendix A), most focusing on the mechanics and kinematics of the faults and their genetic

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2 Used here and in remaining text in reference to fault trace length.
relationship to northeast-striking joints. Most of the studies listed in Appendix A show that
the left-lateral strike-slip faults nucleated and propagated along preexisting joints and that
the faults grew by the linkage of adjacent joints by left-stepping splay cracks. While the
meter-scale faults have been thoroughly analyzed, the regional structure of the 10-km
scale left-lateral strike-slip faults, also common throughout the quadrangle, have not.
Chapter 2 of this thesis and Martel (1990) examine one such fault, and in this paper, we
examine the regional-scale processes that created the m- to km-scale, left-lateral strike-slip
faults.

Joints and strike-slip faults within the Sierra Nevada have long been recognized (e.g.,
Mayo 1941, Moore 1963). They form conspicuous map-scale lineaments that are easily
discernable on aerial photographs, particularly in glaciated, high-elevation areas. It is
commonly accepted that the joints formed from a maximum horizontal compressive stress
oriented northeast–southwest during pluton cooling (e.g., Martel and Pollard 1989;
Bergbauer and Martel 1999). The origin of the left-lateral faults is debated and three end-
member models have been proposed.

(1) Mega kink-band model (Davies and Pollard 1986). In this model, the left-lateral
strike-slip fault zones develop due to the right-lateral kinking of the joints by a
north-northwest-oriented mega kink band, the “Bear Creek kink band” (Davies and
Pollard 1986) (fig. 3-1). The maximum horizontal compressive stress remained at
a constant orientation of 020˚ to 025˚ and the clockwise rotation of the joints
relative to the compressive stress within the kink band led to the formation of the
left-lateral faults (Davies and Pollard 1986). This study elaborates on this model.

(2) Counterclockwise rotation of the maximum horizontal compressive stress
(Martel and Pollard 1989). In this model the joints, formed under a northeast
directed maximum horizontal compressive stress (Martel and Pollard 1989;
Christiansen 1995), were later reactivated as left-lateral faults when the maximum horizontal compressive stress was rotated counterclockwise by ~25°.

(3) Right-lateral shearing by the Rosy Finch shear zone (Tikoff 1994). In this model, the left-lateral faults accommodate late stage deformation on the 80-km long intraplutonic, right-lateral Sierra Crest shear zone system (Tikoff 1994; Tikoff and Saint Blanquat 1997). The left-lateral faults, which have a conjugate orientation to the north-northwest striking Rosy Finch shear zone, correspond to R’ orientation of Riedel-type fracture systems of Logan et al. (1979) (Tikoff 1994).

A few important points of what we know to date about the origin and timing of joints and left-lateral strike-slip faults zones in the central Sierra Nevada include:

1. The strike of the joints vary in each pluton and may be controlled by pluton geometry and thermal stresses associated with pluton cooling (Bergbauer and Martel 1999; Chapter 2 of this thesis);
2. Joint opening, mineralization, and faulting occurred very close in time (Christiansen et al. 1995; Segall et al. 1990; Bergbauer and Martel 1999);
3. The fault zones nucleate and slip along preexisting joints (e.g., Martel and Pollard 1989);
4. In general, meter-scale faults have straight map traces, reflecting the planar geometry of the joints (Martel et al. 1988), whereas the 10-km scale fault zones have a sigmoidal map trace (e.g., Chapter 2 of this thesis); and
5. The origin of the left-lateral faults is unclear (e.g., Tikoff et al. 1998; Christiansen and Pollard 1998).

This chapter provides a regional structural analysis of the joints and faults within the southeast quarter of the Mount Abbot 15’ geologic quadrangle (Lockwood and Lydon 1975), the Mount Hilgard 7.5’ topographic quadrangle (fig. 3-1). We examine the possibility
that preferentially oriented joints created a strong anisotropy within an otherwise relatively homogeneous granitoid and enabled the formation of a 4.8-km wide, at least 5-km long, right-lateral monoclinal kink band with vertical fold axes and north-northwest-striking axial planes. To this end, we quantify the orientations of the kinked joints and faults, provide an estimation of the paleostress direction, and determine the magnitudes of north-south right-lateral displacement across the kink band and northeast-southwest left-lateral slip on faults within the kink band. Sensitivity analysis examines how sources and magnitudes of error affect the estimates of right-lateral kinking and left-lateral slip. The left-lateral slip estimates are compared with field observations of slip on the Gemini fault zone (Chapter 2 of this thesis), an ~10-km long left-lateral strike-slip fault within the Mount Hilgard 7.5’ quadrangle. We then discuss the model in light of the regional tectonic setting and propose that the right-lateral kinking of the joints was responsible for the development of left-lateral strike-slip fault zones that had trace lengths of several meters to tens of meters (e.g., Martel et al. 1988). Some of these faults coalesced into larger fault zones with trace lengths of ~10 kilometers.

Whereas most km-scale kink bands are restricted to thickly bedded rock sequences where bedding provides a mechanical anisotropy (e.g., Powell et al. 1986; Cudahy 1986), the structure discussed here is a km-scale kink band formed in granitic rock, where the kink band foliation is defined by epidote-, chlorite-, and quartz-filled joints and left-lateral strike-slip faults. Active during the waning stages of Late Cretaceous magmatism and subsequently exhumed from 8 to 11 km depth, the structural system described here elucidates the interaction and rapid evolution of structures within oblique-convergent magmatic arcs. Curved lineaments, observed elsewhere in Late Cretaceous plutons of the eastern Sierra Nevada (e.g., Moore, 1963; Lockwood and Moore, 1979), indicate that other km-scale kink bands, or kink-like structures, in the southern Sierra Nevada may have

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3 This list is not intended to be exhaustive of all the conclusions drawn from the work done on the left-lateral faults
accommodated as much as several kilometers of right-lateral displacement (fig. 3-1C and E). If this is true, the km-scale kink band described here may represent a previously unidentified mechanism for accommodating arc-parallel deformation in the cooling portions magmatic arcs.

Geologic Setting

Plutons. The Mount Hilgard 7.5’ quadrangle lies between Yosemite and Kings Canyon National Parks in the east-central Sierra Nevada (fig. 3-1A). The granitoid sequence within the quadrangle is part of the John Muir Intrusive Suite (Bateman 1992) and includes, from west to east, the Bear Dome quartz monzonite, the porphyritic Turret Peak quartz monzonite, the Lamark granodiorite, the Lake Edison granodiorite, and Mono Creek quartz monzonite (Lockwood and Lydon 1975) (fig. 3-2). In general, the granitic bodies are less mafic and decrease in age to the east (Bateman 1992 and references therein) (table 3-1).

The geochronologic data show that each pluton cooled through their hornblende closure temperatures shortly after their crystallization, but that they all passed through the biotite closure temperature at approximately the same time at ~80 Ma. The Lamark pluton crystallized at ~91 Ma and cooled through the hornblende closure temperature of 535±45°C (Bergbauer and Martel 1999, citing Harrison 1981) ~1.4 m. y. later and through the 335±50°C closure temperature of biotite (Bergbauer and Martel 1999, citing Grove and Harrison 1996) after ~11.2 m. y. The data from the Lake Edison pluton show that the pluton crystallized at ~88 Ma and then cooled through the hornblende and biotite closure temperatures ~2 m. y. and ~7 m. y. later. The Mono Creek pluton crystallized at ~86 Ma and then cooled through the hornblende and biotite closure temperatures ~1.5 m. y. and
~5 m.y. later. The similarity of the biotite closure ages likely reflects regional cooling following emplacement of the Mono Creek pluton, the youngest pluton in the study area.

Several lines of evidence constrain the age of the joints and the temperature-pressure conditions during joint opening. The joints in the Mono Creek and Lake Edison granodiorites clearly postdate the intrusion of these two bodies, which have been dated at ~86 Ma and ~88 Ma (table 3-1), respectively. The left-lateral faults in the Lake Edison pluton, that have slipped along the joints, produced metamorphic muscovite that cooled below its closure temperature at ~79 Ma (table 3-1). Epidote, chlorite, and quartz mineralization within the joints indicates mineralization at greenschist facies conditions or temperatures of 300 to 570 °C at pressures of 250 to 500 MPa (Bergbauer and Martel 1999 citing Hyndman 1985). Amphibole geobarometry shows that crystallization pressures across the Sierra Nevada batholith decrease from west to east, and in the Mount Abbot 15' quadrangle crystallization pressures are estimated to be between 2 to 3 kb, or 8 to 11 km) (Ague and Brimhall 1988, their fig. 7). Altogether, these data show that the joints and faults in the Lake Edison pluton formed between 88 Ma and 79 Ma at temperatures of 300 to 570°C and depths of 8 to 11 km.

**Joints.** Segall and Pollard (1983a) show that joints near Florence Lake (fig. 3-1E), filled with chlorite, epidote, sericite, muscovite, calcite, and possibly some zeolites, strike northeast, dip steeply southeast, and range in length from millimeters to tens of meters. Because the age of the joints is closely bracketed by the ages of the plutons and metamorphic muscovite from the left-lateral faults (table 3-1), the joints are interpreted to have formed during the waning stage of Late Cretaceous magmatism. Through thermo-mechanical modeling of the Lake Edison pluton, Bergbauer and Martel (1999) show that the joint orientation can be predicted by determining the tensile stresses acting on the pluton during cooling, the shape of the pluton, and the regional stress conditions.
The analysis of Bergbauer and Martel (1999) is geologically reasonable given the close age relationship between the joints and the plutons. Thermally induced stresses, controlled by pluton geometry and regional stress orientations in a freshly emplaced pluton, would be important in controlling joint orientations. Furthermore, it is reasonable to conclude that the joints in each pluton reflect distinct thermal and regional stress conditions during jointing. It is likely that each pluton would have distinct joint sets that reflect those conditions.

**Fault Zones.** Numerous left-lateral strike-slip fault zones are observed within the quadrangle at the centimeter-, meter-, and km-scale. They form topographic troughs filled with vegetation, snow, or stream channels and appear on aerial photographs as relatively straight or gently curved lineaments (fig. 3-2). Many studies (Segall and Pollard 1983a; Martel et al. 1988; Martel 1990; Bergbauer and Martel, 1999; and Chapter 2 of this thesis) show that the centimeter- and meter-scale faults nucleate and grow along the preexisting joints. Segall and Pollard (1983b) and Martel et al. (1988) show that meter-scale, left-lateral fault propagation did not result in the generation of new fault-parallel fractures, but was the result of the linkage of adjacent joints and indicates that the joints control the geometry of the younger faults. Lim (1998) estimates that 20 to 40 % of the total number of fractures at two study sites in the Bear Creek Valley (fig. 3-2) are reactivated as faults. This emphasizes that most of the quadrangle is characterized by joints and various scales of left-lateral strike-slip fault zones.

**Kink Bands.** Meter- and km-scale right-lateral monoclinal kink bands are observed in the region. Meter-scale kink bands, described and analyzed by Davies and Pollard (1986), are typically 3 to 20 m wide, 5 to 40 m long, and accommodate 1 to 8 m of right-lateral displacement. They are interpreted to have formed within the regional "Bear Creek kink band," a km-scale kink band in the Bear Creek valley (fig. 3-1E) (Davies and Pollard,
The meter-scale kink bands are incorporated into the paleostress analysis presented below.

Davies and Pollard (1986) state that the km-scale Bear Creek kink band is 8-km wide, >15-km long, trends 333˚, and likely formed under a northeast-directed principal stress orientation. Although they describe the dimensions of the kink band, they do not explicitly show its location (Davies and Pollard, 1986). We assume, given their dimensions of the structure, that it consists of all the curved lineaments found in the southern half of the Mount Abbot 15' quadrangle. For this analysis, we subdivide the Bear Creek kink band into an eastern and western half. The joints and faults analyzed in this study compose only part of the Bear Creek kink band of Davies and Pollard (1986) and are termed the eastern Bear Creek kink band (fig. 3-1F). The geographical extent of the eastern Bear Creek kink band used in this study is smaller than described by Davies and Pollard (1986) because this subregion of the larger kink band is the most well-defined, contains the most continuous lineaments, and best displays the angular relationships of the kink band. For brevity, this subsection of the Bear Creek kink band will be described as the “kinked lineaments” or the “eastern Bear Creek kink band.”

Methods and Data

Lineaments were mapped on 1:14,000 scale aerial photos and then transferred to a rectified orthophoto quadrangle at a scale of 1:24,000. The geologic contacts from the Mount Abbot 15' geologic quadrangle (Lockwood and Lydon 1975) were overlain on the Mount Hilgard 7.5’ orthophotograph and the lineament data subdivided in two ways: according to host pluton and structural position within the eastern Bear Creek kink band. The data subsets were then digitized into Rockworks™ for orientation analysis. The mean vector and standard deviation were calculated by isolating the most distinct trends in the data and then calculating the mean from those subsets. The geographical extent of the
eastern Bear Creek kink band was chosen from the area on the orthophotograph where
the kink band was the most clearly defined (i.e., most continuous and easily recognizable).
The implications of selecting these specified geographical limits are examined in the
sensitivity analyses. The paleostress inversions were completed using the techniques
outlined by Srivastava et al. (1998). Observations of outcrop-scale kink bands by Martel
(1999) and Davies and Pollard (1986) were incorporated into the analysis by creating
simplified model kink bands from their published figures and then graphically measuring
the critical angles in the kink band. The displacement analysis was performed by graphical
measurements on the rectified orthophoto quadrangle and then solving for right-lateral
displacement across the kink band and the resulting left-lateral slip on faults within the kink
band using the relationships outlined in Ramsay (1967).

**Analyses**

**Lineament Analysis.** In the high Sierra Nevada, vegetated or snow-filled joints and
fault zones contrast against the glaciated, light colored granitic rocks and make lineaments
easily discernable on aerial photographs. As a consequence, many workers have
analyzed lineaments in glaciated areas above tree line. For example, maps of lineament in
the Marion Peak (Moore 1978), Mount Pinchot (Moore 1963), and Mount Abbot (Lockwood
and Lydon 1975) quadrangles (fig. 3-1C and D). Lockwood and Moore (1979) reveal the
geometry of joints and faults in 15 geologic 1:63,500 quadrangles, ranging from the
Markleeville quadrangle to the Mount Whitney quadrangle (fig. 3-1B). The studies of
Lockwood and Moore (1979) and Moore (1963) are particularly interesting because they
describe lineaments that form broad curves that resemble the curved lineaments observed
in the Mount Hilgard 7.5' quadrangle. While no distinct km-scale kink bands are readily
observed on the maps and figures of Lockwood and Moore (1979) and Moore (1963) (fig.
3-1C and D), the occurrence of the curved lineaments suggests that the process of kinking or bending is not unique to the Mount Hilgard 7.5’ quadrangle.

In this study, we focus our analysis on the southeast quarter of the Mount Abbot 15’ geologic quadrangle (Lockwood and Lydon 1975), the Mount Hilgard 7.5’ topographic quadrangle, where the lineaments in the north-central portion of the quadrangle make a broad bend from ~070° to 030° (fig. 3-1E and F; fig. 3-2). The 3197 lineations analyzed in this area (fig. 3-3) are treated as bidirectional and are discussed below with reference to their northern hemisphere azimuths.

Analysis A – Plutons. Lineations within the Lamark and Turret Peak plutons, 1001 in total, trend dominantly northeast, ranging from ~350˚ to 050˚ (fig. 3-4A, table 3-2). Although the lineament data are largely from the Lamark and Turret Peak plutons, the Bear Dome quartz monzonite and miscellaneous metavolcanic rocks contribute ~3% of the observations in the “Lamark and Turret Peak” data set (fig. 3-4A). Within the Lake Edison pluton, 897 total lineaments trend northeast and east-northeast (~020 to 070˚) with most data clustering at 060˚ (fig. 3-4A). The 1299 lineations measured within the Mono Creek pluton cluster at one dominant trend of 030˚ (fig. 3-4A).

Lineament length frequency for the data subdivided by host pluton (fig. 3-5A) indicates that most of the lineaments range in length between ~25 and ~500 m, with most lineaments being ~100 to 150 m in length. All data are positively skewed, indicating a non-normal distribution or a possible digitizing bias. That is, lineaments that crossed large snow patches or vegetation were digitized as two or more segments rather than one long lineament. Consequently, some longer lineaments, punctuated by snow or vegetation, may be represented as several short lineaments. There are no discernable relationships between the host pluton and the lengths of the lineaments.

Analysis B – Kink Band. When subdivided by structural position within the Bear Creek kink band (fig. 3-4A, table 3-2), the data display many of the same trends observed when
divided by host pluton. In the northeast limb of the kink band, formed in the Mono Creek pluton, over 16% of the 897 lineaments show a dominant trend of \(-030^\circ\). These lineaments, observed throughout the Mono Creek pluton, have not been rotated during kink band deformation and are interpreted to reflect the regional joint and fault trend. Within the kink band (i.e., "INNER LIMB", fig. 3-4B), 925 lineaments display a range of orientations, but clearly show a dominant trend at \(-050^\circ \) to \(-070^\circ \). In the southwest limb of the kink band, the data displays two dominant orientations, \(-350^\circ \) and \(-065^\circ \). The \(-020^\circ \) trend of the southwestern limb of the Bear Creek kink band that is evident in the southwest part of the Mount Abbot 15' quadrangle (fig. 3-1E) is not well represented in the data and may be due to the limited exposure of the western half of the kink band in the Mount Hilgard 7.5' quadrangle (fig. 3-1E and F).

The length histograms for lineaments subdivided by structural position within the kink band display similar characteristics as those lineaments subdivided by host pluton (fig. 3-5B). In general, the lineament distribution is positively skewed and lengths range from 0 to \(>700\) m. Most lineaments are 100 to 160 m long.

To summarize, the curved nature of the joints and faults observed within the Mount Hilgard 7.5' quadrangle is clearly shown in the two orientation analyses. The regional joint trend of \(-030\pm10^\circ\), identified from the undeformed northeast limb of the kink band and surrounding Mono Creek pluton (fig. 3-4A and B), is best expressed in the NE quarter of the quadrangle where over 660 lineaments create a strong northeast trend. The regional joint trend becomes deflected to \(-050\) to \(-070^\circ\) in the western part of the Mono Creek and eastern part of the Lake Edison plutons. This area corresponds to the inner limb of the eastern Bear Creek kink band. To the west and southwest, the lineaments show a wide variety of orientations. Trends are apparent at \(-350^\circ\) and \(-060^\circ\). The lineaments, subdivided by host pluton and position relative to the kink band, range in length from \(<10\) m to \(>750\) m, with most of the lineaments having lengths between \(-100\) and \(-160\) m.
Paleostress Analysis. Kink bands, common in rocks and minerals with strong anisotropic fabrics or cleavage, are typically 1 mm to several meters in width and exhibit angular geometries (Ramsay and Huber 1987). The simple geometry of kink bands allows easy analysis of their kinematic origin and inferred stress directions (Johnson 1977; Suppe 1995).

The basic geometry of a hypothetical kink band can be described using three angles ($\phi$, $\phi_k$, and $\psi$; fig. 3-6) that must add up to 180˚ (Anderson 1968). Because kink bands grow with well-defined geometrical relationships, these structures can be used to determine paleostress orientations (e.g., Gay and Weiss 1974). One technique used to invert paleostress orientation is the kink band triangle method of Srivastava et al. (1998). This technique combines graphically determined angles from the kink band in question with experimentally derived relationships between kink band geometry and the orientation of the maximum compressive stress. Once combined, the orientation of the paleostress direction can be read from a ternary diagram (fig. 3-7).

Eight semicontinuous lineaments from the Mount Hilgard 7.5’ quadrangle and 26 meter-scale lineaments from the Hilgard Branch (Martel 1999), the Kip Camp, and the Trail Fork outcrops (Davies and Pollard 1986) within the Bear Creek drainage (northwest quarter of the Mount Hilgard 7.5’ quadrangle), are used in this analysis (fig. 3-8). Simplified lineament and outcrop sketches are used to create model kink bands, which in turn are used in the paleostress estimations (fig. 3-9). The model kink bands represent angular, straight-line simplifications of the kink bands and are prone to error. We include data from the outcrop-scale kink bands described by Martel (1999) and Davies and Pollard (1986) to determine if the regional stress field determined from the paleostress analysis is similar to the paleostress direction for the km-scale kink band.

The measured limb angles (table 3-3; fig. 3-9) show that the majority of the data do not plot on the paleostress line and must be projected onto the line for paleostress estimation.
Projection techniques are outlined in Srivastava et al. (1998). Sixteen out of 19 data points from the meso-scale kink band of Davies and Pollard (1986) and three out of seven data points from Martel (1999) project onto the paleostress line and indicate an average $\sigma_1$ orientation of 053˚ (table 3-3). Three out of eight data points from the Mount Hilgard 7.5’ quadrangle project onto the paleostress line. These three data points indicate $\sigma_1$ orientations of 025˚, 032˚, and 031˚. The remaining data do not plot onto the line and could not be used in the analysis.

The overall north-northwest trend of the km-scale kink band suggests that a generally northeast-directed, maximum compressive stress is required to generate the eastern Bear Creek kink band. It is likely, given the results of this analysis and the orientation of the kink band limbs relative to north (fig. 3-8), that these structures formed under the same maximum, horizontal compressive stress and, as hypothesized by Davies and Pollard (1986), that the meter-scale kink bands became rotated within the limbs of the larger Bear Creek kink band. This process has also been documented in km-scale kink bands in Australia, where meter-scale kink bands become rotated within the limbs of km-scale kink bands (e.g., Cudahy 1986).

**Displacement Analysis.** The unique map pattern created by the joints and faults in the Mount Hilgard 7.5’ quadrangle provides an opportunity to calculate an estimate of the north-south, right-lateral displacement (“D”, fig. 3-6) that has occurred across the km-scale kink band. It is also possible to calculate an estimate of the northeast-southwest, left-lateral slip (“d”, fig. 3-6) accommodated on the joints and faults as a result of the right-lateral displacement. These estimates, generated through a simplified kink band model, can be used to test various hypotheses for the formation of the kinked joints and faults and can be compared to the slip measured on various scales of left-lateral faults within the quadrangle. As an example, if the joints and faults originally started out straight and were later kinked to their present geometry, we can address questions such as how much left-
lateral slip would occur on the faults within the kink band? Are these estimates realistic in light of the field data?

The calculations are made through trigonometric solutions of the simplified model of the eastern Bear Creek kink band using equations outlined in Ramsay (1967) and solved by W. L. Taylor (pers. comm.). For a hypothetical right-lateral monoclinal kink band, the magnitude of right-lateral displacement (see fig. 3-6) can be calculated as:

\[ D_{right-lateral} = 2W \cdot TAN\left(\frac{180 - A}{2}\right) \]  

(1)

where: \( w = \) width of the kink band and \( A = \) the angle between the internal and external foliations.

Both \( A \) and \( W \) can be measured directly from the kink band (fig. 3-6) if the plane of exposure is orthogonal to the internal and external foliations. The magnitude of left-lateral slip on the fault planes that compose the foliation can be determined:

\[ d_{left-lateral} = 2S \cdot COT\left(\frac{A}{2}\right) \]  

(2)

where: \( S = \) the average slip surface spacing and \( A = \) the angle between the internal and external foliations.

These starting solutions assume:

(1) The kinked joints and faults observed in the Mount Hilgard 7.5' quadrangle can be decomposed into simplified, straight-line kink band models. This is likely to be the largest assumption made during the analyses. Many of the joints and faults change orientation through broad curves (fig. 3-2), rather than abrupt angular transitions characteristic of outcrop- and thin section-scale kink bands. It is certain that some error is incorporated into the calculations by making this simplifying assumption;

(2) There are 26 primary slip surfaces within the part of the Bear Creek kink band being analyzed. This estimate is based on the average number of snow- or
vegetation-filled lineaments visible on the 1:24,000 orthophotograph on six north-south transects across the study site on the eastern half of the Bear Creek kink band. While the model assumes that the 26 surfaces are continuous through the kink band, inspection of the orthophotograph indicates that this is clearly not the case. Snow- or vegetation-covered lineaments tend to be discontinuous and the joints and faults typically have surface trace lengths of ≤800 m. Field investigation shows that most, but not all, snow bound troughs are left-lateral strike-slip fault zones. Some are joints without shear displacement (S.J. Martel pers. comm.). Despite this, we feel that this estimation is appropriate because our structural investigation of km-scale, left-lateral faults in this area (Martel 1990; Chapter 2 of this thesis) shows that many of the faults are linked to other fault zones, which effectively creates continuous slip surfaces. Below, we discuss the sensitivity of the results to this estimate and evaluate the range of left-lateral slip estimates by varying the number of fault surfaces;

(3) There is no dilation or contraction within the kink band;

(4) Strain within the kink band results in left-lateral slip on the faults and no deformation is taken up internally between the faults; and

(5) All left-lateral deformation is evenly distributed among the slip planes.

(6) The kink band has fixed hinges.

With the preceding assumptions in mind, we calculate magnitudes of right-lateral displacement across the kink band and the magnitudes of left-lateral slip on the faults within the kink band (table 3-4A). For the case outlined here, we estimate the amount of right-lateral displacement across the kink band to be ~3680 m and the left-lateral slip on each of the 26 faults within the kink band to be ~148 m. These solutions assume an angle A of 136°, 26 faults within the kink band, and a kink band length and width of 5000 m and
4800 m, respectively. The sensitivity of the calculation to these parameters is discussed below.

Although we have no data to quantitatively compare the right-lateral displacement estimates for the kink band itself, the 148-m left-lateral-lateral slip estimate seems reasonable when compared to the slip data compiled for the Gemini fault zone (Chapter 2 of this thesis), which is one of the 26 prominent kinked lineaments used in the slip estimation. Chapter 2 of this thesis documents an average slip of ~44 m and a maximum left-lateral slip of ~130 m on the western half of the Gemini fault zone. The estimation calculated here, therefore, is high, but reasonable in light of the field data presented in Chapter 2 of this thesis.

**Sensitivity Analysis.** We perform sensitivity analyses to determine how measurement errors affect the estimated magnitudes of slip across the kink band and on left-lateral strike-slip faults in the kink band (fig. 3-10). For our simplified kink band model, four variables could introduce error into the displacement estimates: the kink angle \( A \), the number of slip surfaces within the kink band \( L/S \), the kink width \( W \), and the kink length \( L \) (see fig. 3-6). Error in the kink angle \( A \) and the kink band width \( W \) affect the magnitude of right-lateral displacement across the kink band, while error in the number of slip surfaces \( L/S \) and the length of the kink band \( L \) affect the magnitude of left-lateral slip on faults within the kink band (see fig. 3-6 and equations 1 and 2).

**Error Estimating Angle \( A \).** The model results are calculated with an angle \( A \) of 136°. This number was determined by graphically measuring the model kink band created from the lineament analysis. We estimate the largest possible variation in measurement of \( A \) to be 30° (130 to 160°). For 26 left-lateral faults accommodating the slip within the kink band and a kink band length and width of 5000 m and 4800 m, respectively, the estimated range of right-lateral displacement across the kink band is 1692 to 4476 m and the estimated range of left-lateral slip within the kink band is 68 to 179 m (fig. 3-10A; table 3-4B).
Error Estimating Number of Faults. To evaluate the sensitivity of the number of faults on the magnitude of left-lateral slip for a fixed angle $A$ of 136˚, we consider two end-member conditions, slip accommodated on 6 or 37 slip surfaces (fig. 3-10B; table 3-4B). These end-member conditions are derived from considering only the largest, most continuous lineaments visible within the kink band and taking the highest number of major lineaments observed on the six north-south transects. Considering these two end-member possibilities, we calculate that the estimated left-lateral slip on the lineaments may range from 104 to 640 m.

We consider an extreme end-member situation where only the meter-scale faults accommodate the displacement within the kink band (inset fig. 3-10B). Lim (1998, fig. 42) illustrates that the meter-scale faults have a spacing of approximately 2.4 m at the Reflecting Bowl site in the Bear Creek Valley (fig. 3-2). Assuming a fault spacing of 2.4 m and a kink band length of 5000 m (see discussion of this parameter below), we calculate that the right-lateral displacement across the kink band is 3685 m and left-lateral slip on meter-scale faults within the kink band is 1.8 m (inset fig. 3-10B).

Error Estimating Kink Width. Estimation of the east-west width of the kink band, $W$ (fig. 3-6), can also lead to errors in the displacement estimates. In the calculations, we estimate the width of the fault zone to be 4800 m. To investigate the sensitivity of this parameter on the estimate, we consider end-member situations where the width ranges from 4500 to 6250 m. Considering this range for an angle $A$ of 136˚, we calculate a minimum and maximum right-lateral displacement of 3455 m and 4798 m, respectively (fig. 3-10C; table 3-4B).

Error Estimating Kink Length. The length, $L$ (fig. 3-6), of the kink band affects the magnitude of left-lateral displacement calculated on the slip surfaces within the kink band (equation 2). The model assumes a kink band length of 5000 m. This is also a lower end-member condition, meaning that we do not think the kink band could be less than 5000 m
long. To calculate slip for the upper bounds of this parameter, we estimate that the kink band length may be as long as 6120 m. Using this as an upper end-member condition and assuming 26 left-lateral strike-slip surfaces, we calculate that left-lateral slip may be as high as 180 m on each slip surface (fig. 3-10C; table 3-4B).

As an extreme, we calculate the magnitude of right-lateral displacement across the kink band and the magnitude of left-lateral slip on faults within the kink band using the highest and lowest values of each of the four parameters (table 3-4C). The highest and lowest magnitudes of right-lateral slip across the kink band are ~5.6 and ~1.6 km, respectively. The highest and lowest magnitudes of slip on left-lateral strike-slip faults within the kink band are 951 and 47 m, respectively. Although these values are extremes, they are still within a reasonable order of magnitude.

To summarize, the sensitivity analyses indicate that, by incorporating the widest margins of error for four kink band parameters, the cumulative magnitude of right-lateral displacement across the kink band ranges between 1587 to 5596 m and the magnitude of left-lateral slip on faults within the kink band ranges between 47 to 951 m (table 3-4C). Although some of these estimates appear high, they are reasonable order of magnitude estimates. Below we discuss the implications of these estimates in light of previous work in the area.

**Other Displacement Constraints.** Ross (1988) examined the question of the possible amount of lineament rotation in the region through paleomagnetic analyses across the western half of the Bear Creek kink band. She shows that 13.4±7° of vertical rotation of the 020° striking, southwestern kink band limb has occurred below the 500±50°C paleomagnetic blocking temperature (Ross 1988). The conclusions of Ross (1988) are based on analysis of 73 cores collected from 22 sample sites on the western Bear Creek kink band (see fig. 3-1E for site locations). One or two specimens from each core were analyzed using thermal demagnetization and alternating field demagnetization in a
cryogenic magnetometer (Ross 1988). The carriers of magnetization were not described. The resulting vector component plots displayed linear trends, indicating that a single component of magnetization was isolated (Ross 1988). Approximately 80% of the samples exhibited a stable component of magnetization (Ross 1988). Ross (1988) concludes that only ~6° to 20° of rotation could have occurred below the paleomagnetic blocking temperature. Ross (1988) suggests that the kinked-lineament geometry observed in the study area formed as a result of continuous deformation as the rocks cooled. Ross (1988) does indicate that APW, thermal remagnetization, or a small sample population may limit her the breadth of her results. The location of Ross’ (1988) sample locations are close to the hinge area of the kink band and not well suited to test for the maximum amount of inner limb rotation. Sample locations further to the east may have recorded more inner limb rotation than her analyses suggest.

Bergbauer and Martel (1999) illustrate how the orientation of cooling joints can be directly related to thermal stress and the pluton geometry. One conclusion of their work is that, for the Lake Edison pluton, the observed curvature of joints and faults can be explained by superimposing the regional uniform stress field and the predicted thermal stresses from the cooling pluton (Bergbauer and Martel 1999). The resulting map of predicted joint orientation broadly resembles the joints and faults within the Lake Edison pluton (fig. 3-11). Thus, one possibility is that the northwest–southeast elongate geometry of the plutons in the study area may have imparted a tendency for northeast-striking joints to subtly changed orientations (± 30°) within each pluton. That is, thermal stresses within the plutons formed joints whose orientations varied by ~30° across the study area. This variation produced a sigmoidal map pattern that was later modified by 13.4±7° of right-lateral kinking. If this is true, the magnitude of right-lateral kinking is much less than simple restoration of the joints and faults would suggest.
To examine the range of possible original joint orientations, we calculate the magnitude of right-lateral displacement across the kink band and left-lateral slip on faults within the kink band by examining 13.4±7° of rotation. The model assumes that the original orientation of the joints in the innerlimb of the kink was 062° ± 7° (075°, which is the present modeled orientation minus 13±7°, the Ross (1988) rotation estimate; fig. 3-12). Performing the calculations for the magnitude of right-lateral displacement across the kink band and left-lateral slip on faults within the kink band (assuming 26 slip surfaces and an angle A of 136°) yields estimates of 1126 m and 45 m, respectively (table 3-5). Considering the ± 7° margin of error in the estimate of Ross (1988), we calculate that the right-lateral slip across the kink band could range from 573 to 1838 m and the left-lateral slip on faults within the kink band could range from 23 to 73 m (table 3-5).

The displacement data for the ~10-km long Gemini fault zone (Chapter 2 of this thesis) provides field-based constraints on these calculations. Displacement on the Gemini fault zone ranges from 0 at its tips to 131 m on the western segment. The average displacement is ~44 m. This average is compatible with the left-lateral slip estimate that we calculate for the eastern Bear Creek kink band using the paleomagnetic data of Ross (1988).

To summarize, we calculate an estimated right- and left-lateral displacement for the eastern Bear Creek kink band by assuming that the initial joint pattern was kinked. We calculate the magnitude of right-lateral displacement across the kink band and left-lateral slip on faults within the kink band by rotating the kinked joints by 13±7°. The results show that the magnitudes of right- and left-lateral displacement are 1126 m and 45 m. Including the ±7° error, the right-lateral displacement across the kink band could range from 573 to 1838 m and the range of left-lateral slip on faults within the kink band could range from 23 to 73 m. Field data from the Gemini fault zone shows that the average left-lateral slip along the ~10-km trace length is ~44 m (fig. 2-9, Chapter 2 of this thesis) and indicates that
the $13\pm 7^\circ$ of limb rotation estimated by Ross (1988) is geologically reasonable. This suggests that the joints, whose strikes may have originally varied by as much as $\sim 30^\circ$ in the three plutons, were later modified by map-scale kinking that resulted in some joints slipping to form left-lateral strike-slip faults.

**Interpretation and Discussion**

The structures of this region indicate that Late Cretaceous northeast-directed subduction in central California resulted in a short, complex structural history that included pluton emplacement, ductile shearing, cooling, and the formation of joints, a map-scale kink band, and brittle left-lateral strike-slip faults. The process of late-stage, arc-parallel deformation accommodated on the Bear Creek kink band is likely to have occurred elsewhere in the Late Cretaceous magmatic arc. The observation of curved lineaments in Late Cretaceous plutons in the southern Sierra Nevada (e.g. Moore, 1963; Lockwood and Moore, 1979) (fig. 3-1 C and D) suggest that the process of kinking observed in the Mount Hilgard 7.5’ quadrangle may have occurred elsewhere. By focusing on a small component of a potentially previously unrecognized batholith-scale process, this study examines the details and feasibility of kink band formation in granitic plutons.

One controversy in the Mount Hilgard 7.5’ quadrangle concerns the presence and structural significance of the Rosy Finch shear zone. Tikoff (1994) argues that the Rosy Finch shear zone is part of the Sierra Crest shear-zone system (SCSZS), a series of discontinuous shear zones that extend the entire length of the range and represent right-lateral strike-slip partitioning within the transpressive Late Cretaceous magmatic arc (fig. 3-13). Greene and Schweickert (1995) conclude that the SCSZS is comprised of, from north to south, the Gem Lake shear zone (Greene and Schweickert 1995), the Rosy Finch shear zone (Tikoff 1994; Tikoff and Saint Blanquat 1997; Tikoff and Greene 1997), and the Proto
Kern Canyon shear zone (Busby-Spera and Saleeby 1990; Greene and Schweickert 1995) (fig. 3-13). Tikoff (1994) argues that the SCSZS is >300-km long, ≤ 3-km wide, and exhibits syn- and post-magmatic brittle-ductile to ductile deformation. It is unclear how much cumulative displacement has occurred along the system because of the problems associated with over-printing and accommodation of slip by molten rock (e.g., Tikoff and Saint Blanquat, 1997). Busby-Spera and Saleeby (1990) estimate that, for the Proto Kern Canyon shear zone, the component of strike-slip motion is more than four times the component of dip-slip movement. Using these estimates and lithologic constraints of the dip-slip component of the Proto Kern Canyon shear zone, Busby-Spera and Saleeby (1990) argue that the minimum displacement for the Proto Kern Canyon shear zone (southern SCSZS) must be ≥ 40-km.

Tikoff (1994) and Tikoff and Saint Blanquat (1997) indicate that the Rosy Finch shear zone is characterized by a broad band of subvertical mica folia and shallily plunging lineations defined by elongate quartz grains. Tikoff (1994) reports dextral sense-of-shear indicators that include imbricated porphyroclasts, folded aplite dikes, and displaced feldspar cleavages. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of metamorphic biotite and hornblende, from where the shear zone deformed the Lake Edison pluton in the Bear Creek valley, yield ages of 83.7±0.4 Ma and 87.3±0.2 Ma, respectively (Tobisch et al. 1995) (table 3-1). Tikoff and Teyssier (1994), based on modeled porphyroclast rotation, estimate up to 8-km of solid-state, right-lateral offset along the Rosy Finch shear zone, with an unspecified amount of slip occurring during magmatic deformation. The minimum amount of right-lateral offset on the shear zone is thought to be constrained by the 1.2-km, right-laterally faulted contact of the Lamark and Turret Peak plutons on the south-central margin of the Mount Abbot 15’ quadrangle (Tikoff, 1994) (fig. 3-2).
The nature of the Rosy Finch shear zone is currently debated (e.g., Christiansen and Pollard, 1998; Tikoff et al., 1998; S.J. Martel, pers. comm.). The main lines of evidence to support the presence of the Rosy Finch shear zone include:

1. The recognition of a prominent north-striking foliation and vertical stretching lineation in the Lamark, Lake Edison, and Mono Creek plutons (Sherlock and Hamilton 1958; Lockwood and Lydon 1975; Tikoff 1994). The foliation strikes at an acute angle to the magmatic foliation and, in certain areas of the Lake Edison and Lamark plutons, is more prominent than the magmatic foliation;

2. The identification of two other shear zones in the eastern Sierra Nevada that cut Late Cretaceous plutons and are along strike of the Rosy Finch shear zone (i.e., the Gem Lake shear zone of Greene and Schweickert, 1995 and the Proto Kern Canyon fault zone of Busby-Spera and Saleeby, 1990). These shear zones show similar foliations and lineations and have more obvious offset markers;

3. Microstructural and anisotropy of magnetic susceptibility studies of Tikoff and Saint Blanquat (1997) and Tikoff and Teyssier (1994) document right-lateral sense-of-shear indicators and right-laterally deflected magnetic foliations within the Mono Creek pluton; and

4. The occurrence of meter-scale, right-lateral brittle fault zones in the south-central margin of the Mount Abbot 15' quadrangle. Tikoff (1994) interprets these structures as being areas of strain localization formed during the waning phases of right-lateral movement along the Rosy Finch shear zone.

The arguments against the occurrence of the Rosy Finch shear zone as a significant tectonic element are summarized as follows:

1. The lack of discernable offset markers along the trace of the shear zone (S. J. Martel pers. comm.). Eight km of right-lateral, solid-state displacement should offset the pluton contacts; however, the only documented pluton offset is the
proposed 1.2-km right-laterally offset Lamark / Turret Peak contact (fig. 3-2). The younger Lake Edison and Mono Creek contact does not appear to be offset along the shear zone (fig. 3-2);

(2) lack of clear field evidence for the shear zone (Christiansen and Pollard 1998). In the Mono Creek pluton, the Rosy Finch shear zone is weakly expressed through a foliation defined by the alignment of magnetic minerals. The foliation is not generally recognized at the outcrop or hand-sample scale; and

(3) the mechanics of simultaneous right-lateral shearing, jointing, and left-lateral faulting, as proposed by Tikoff (1994), are inconsistent and improbable (S.J. Martel pers. comm.). Tikoff (1994) suggests that the left-lateral brittle faults and the waning stages of right-lateral shearing on the Rosy Finch are synchronous.

Extensive work on the left-lateral faults shows that the faults slip along preexisting joints and that the joints cut the poorly developed foliation of the Rosy Finch shear zone (e.g., Chapter 2 of this thesis). If the Rosy Finch postdates the joints, then the shear zone could not be related to pluton emplacement and a complete reevaluation of the structure is needed. If the Rosy Finch shear zone and joints developed simultaneously, the joints, which are nearly to orthogonal to the Rosy Finch shear zone, were being right-laterally sheared and would have slipped left-laterally and could not have opened as joints (S.J. Martel pers. comm.).

Proposed Tectonic Model. In light of the above points, we discuss two end-member models, Model A and B, that could explain the kinked joints and faults observed in the Mount Hilgard 7.5’ quadrangle.

Model A. The kink band and the Rosy Finch. In this model, the kinked lineaments in the Mount Hilgard 7.5’ quadrangle form solely from right-lateral kinking accomplished by the waning stages of right-lateral shear along the Rosy Finch shear zone or its related tectonic elements. In this model, the joints originally formed straight, parallel lineaments
that crossed the three plutons without changing orientation. Once formed, the joints were right-laterally kinked along a zone parallel to the Rosy Finch shear zone by as much as ~3.7-km (the magnitude of right-lateral displacement across the kink band, assuming initially straight joints; table 3-4A). In this model, the kinked joints and faults observed in the Mount Hilgard 7.5' quadrangle are formed solely by kinking that is driven by the waning stages of right-lateral shear along the Rosy Finch shear zone. If this model is correct up to 5.6 km of right-lateral, late-stage deformation could have been accommodated in the Late Cretaceous Sierran arc by kinking.

**Model B. The apparent kink band.** In this model (fig. 3-14), the joints are only right-laterally kinked ~1.1-km in the vicinity of the Rosy Finch shear zone as a result of northeast-directed compression in a similar manner to that originally discussed by Davies and Pollard (1986). Applying the results of the paleomagnetic data of Ross (1988) and the thermal modeling of Bergbauer and Martel (1999), the model suggests that the joints in the Lamark, Lake Edison, and Mono Creek plutons did not form straight lineaments across these plutons. Rather, they had curved traces that reflect the distinct geometry and thermal and regional stress conditions during pluton cooling (e.g., Bergbauer and Martel 1999). Shortly after crystallization of the Mono Creek and Lake Edison plutons, joints opened normal to the least compressive stress. This is supported by the radiometric dating of the minerals within the plutons and within the left-lateral fault zones (see geologic setting above; table 3-1; fig. 3-15). The jointed plutons cooled rapidly and kinked in response to northeast directed compression in the vicinity of the thermally weakened, inactive Rosy Finch shear zone (fig. 3-15). The paleostress analysis, presented in the study, suggests that the stress was oriented N29°E to N53˚E. This is consistent with plate reconstruction for the Late Cretaceous, which shows northeast-directed subduction (Stock and Molnar 1988). This model implies that the rocks involved in the kink-band deformation must have been cool enough to fail brittlely under tensile stresses (i.e., joint), yet be warm
enough to bend slightly 6 to 20˚ (from the kink band modeling) into a kink band. These conditions could be encountered if there were steep thermal gradients, such as during rapid unroofing of a freshly emplaced pluton. It is likely that the location of the Rosy Finch shear zone would have been considerably warmer and thus, mechanically weaker than the surrounding rocks, making this area the locus of kinking. If the results of Ross (1988) are correct, rotation of the innerlimb of the kink band by 6 to 20°, as shown by our modeling, recreates the observed slip on the km-scale, left-lateral fault zones and suggests that this model is a simple, yet reasonable, explanation of the structures in the area.

Model B couples the kinked joints and left-lateral strike-slip faults, and the occurrence of the Rosy Finch shear zone into a single tectonic model that honors the field data, our understanding of the mechanics of the structure, and the kinematics of the kink band and left-lateral faulting. For example, the microstructures observed along the Gemini fault zone (Chapter 2 of this thesis) are characterized by brittle deformation everywhere along the fault zone except where the fault zone cuts the Rosy Finch shear zone. Tikoff and Saint Blanquat (1997) state that the Rosy Finch shear zone is characterized by high temperature, ductile deformation. This evidence suggests that the Rosy Finch shear zone and the Gemini fault zone did not form synchronously and it is likely that the spatial correlation between the Rosy Finch shear zone and Bear Creek kink band is a result of the area being warmer, and thus mechanically weaker, than the surrounding rocks.

Regardless of which model is correct, the original point of this paper is that a km-scale, right-lateral monoclinal kink band is a plausible mechanism for the formation of the left-lateral strike-slip faults in the region and for accommodating north-south right-lateral slip. The occurrence of the kinked lineaments in the Mount Hilgard 7.5’ quadrangle and the observation of curved lineaments in other quadrangles (i.e., Moore 1963; Lockwood and Moore 1978; fig. 3-1) indicates that the complex interactions of right-lateral shearing, pluton cooling, jointing, km-scale kinking, and left-lateral faulting observed in the Mount Hilgard
7.5' quadrangle may have occurred elsewhere within the Late Cretaceous Sierra Nevada magmatic arc. If this is true, km-scale, right-lateral kinking accommodated late-stage, arc-parallel slip and may be a deformation process, responsible for up to 5.6 km of late-stage, right-lateral deformation that has been previously unrecognized in oblique-convergent magmatic arcs.

Conclusions

The kinked faults and joints that compose the north half of the Mount Hilgard 7.5' quadrangle are part of a 4.8-km wide, right-lateral monoclinal kink band that may have accommodated as much as 5.6 km of right-lateral slip within the transpressive Late Cretaceous magmatic arc. The faults and joints strike 020° to 030° on the northeast limb of the kink band and strike ~070° within the kink band. The eastern Bear Creek kink band may have accommodated between 1.6 and 5.6 km of right-lateral kinking and individual left-lateral strike-slip faults within the kink band may have slipped between 47 and 951 m. Combined with the estimates of 13.4±7° of rotation by Ross (1988), the model shows that 1.1 km of right-lateral displacement across the kink band is required to generate ~44 m of left-lateral slip on 26 faults, including the Gemini fault zone, a ~10-km long left-lateral strike-slip fault zone within the kink band. If the results of Ross (1988) are correct, the original fault and joint orientation may have had a kinked map pattern, which was further rotated 6 to 20° by kinking. Our sensitivity tests on the model parameters (i.e., width, height, length, and angle between internal and external joints) indicates that the calculations are reasonable order-of-magnitude estimates. The simplified model of the kink band provides a structurally coherent explanation that honors the field observations of the joints, faults, and the occurrence of the Rosy Finch shear zone.
Our analysis of the structures from the Mount Hilgard 7.5' quadrangle, active shortly after the emplacement of the youngest plutons within the Late Cretaceous Sierran arc, elucidate processes operative over a small component of a much larger structural system. While some of these structures have small displacements, taken together, the joints and faults, resulting from pluton cooling and kinking, can form map-scale fracture and fault meshes (e.g., Sibson 1995) that could be an important system for fluid flow at <10 km depths and provide insight into structural processes occurring in active oblique-convergent margins.

REFERENCES CITED


Davies, R. K., and Pollard, D. D. 1986. Relations between left-lateral strike-slip faults and


Tikoff, B., and Blanquat, M. S. 1997. Transpressional shearing and strike-slip partitioning
in the Late Cretaceous Sierra Nevada magmatic arc, California. Tectonics 16:442-459.


Table 3-1. Summary of Geochronology for the Plutons and Faults within the Mt. Hilgard 7.5' Quadrangle.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Age</th>
<th>Method</th>
<th>Material</th>
<th>Source</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamark Pluton</td>
<td>91.9±0.6 Ma</td>
<td>U/Pb</td>
<td>Zircons</td>
<td>Coleman et al. 1995</td>
<td>Crystallization age</td>
</tr>
<tr>
<td></td>
<td>80.0±0.2 Ma</td>
<td>40Ar/39Ar</td>
<td>Biotite</td>
<td>Bergbauer and Martel 1999</td>
<td>Cooling age</td>
</tr>
<tr>
<td></td>
<td>90.3±0.7 Ma</td>
<td>40Ar/39Ar</td>
<td>Hornblende</td>
<td>Bergbauer and Martel 1999</td>
<td>Cooling age</td>
</tr>
<tr>
<td>Lake Edison Pluton</td>
<td>88.0±1 Ma</td>
<td>U/Pb</td>
<td>Zircons</td>
<td>Tobisch et al. 1995</td>
<td>Crystallization age</td>
</tr>
<tr>
<td></td>
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<td>Hornblende</td>
<td>Bergbauer and Martel 1999</td>
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<td>Hornblende</td>
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<tr>
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<td>Biotite</td>
<td>Bergbauer and Martel 1999</td>
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<td>Bergbauer and Martel 1999</td>
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<td>Zircons (?)</td>
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<td>Zircons (?)</td>
<td>Tikoff and Saint Blanquat 1997 citing personal communication with B. Carl, 1996</td>
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<td>Hornblende</td>
<td>Tobisch et al. 1995</td>
<td>Cooling age</td>
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</tbody>
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Note. The asterisk represents the most commonly accepted age of pluton
### Table 3-2. Summary Statistics for the Lineaments of the Mt. Hilgard 7.5’ Quadrangle.

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<tr>
<th>Method of subdivision</th>
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Table 3-3. Kink-Band Angles and Inferred Paleostress Direction for the Mt. Hilgard
Lineaments, the Hilgard Branch Outcrop (Martel, 1999), and the Kip Camp and Trail
Fork Outcrops of Davies and Pollard (1986). See Fig. 3-2 for Outcrop Locations.

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<th></th>
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### Table 3-4. (A) Initial Calculations of Displacement Estimates and Associated Parameters. (B) for the Initial Calculation Error Ranges from Four Sources of Error (See Figure 3-10).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values used in calculation</th>
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<tr>
<td><strong>A. Initial slip estimates</strong></td>
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<tr>
<td>Right-lateral displacement</td>
<td></td>
</tr>
<tr>
<td>across kink band</td>
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</tr>
<tr>
<td>Left-lateral slip on</td>
<td></td>
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<tr>
<td>faults within kink band</td>
<td></td>
</tr>
<tr>
<td>Angle A (˚)</td>
<td>136</td>
</tr>
<tr>
<td>Number of faults</td>
<td>26</td>
</tr>
<tr>
<td>kink band width (m)</td>
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</tr>
<tr>
<td>kink band length (m)</td>
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<tr>
<td><strong>B. Error estimates</strong></td>
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<tr>
<td>1692 - 4476</td>
<td>68 - 179</td>
</tr>
<tr>
<td>-</td>
<td>104 - 640</td>
</tr>
<tr>
<td>3455 - 4798</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>148 - 180</td>
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<tr>
<td>1692 - 4798</td>
<td>68 - 640</td>
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<tr>
<td>Cumulative slip range (m)</td>
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<td>5000 - 6120</td>
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### Table 3-5. Maximum and Minimum Slip Estimates Using the Highest and Lowest Values for Four Parameters.

<table>
<thead>
<tr>
<th>Right-lateral displacement across kink band</th>
<th>Left-lateral slip on faults within kink band</th>
<th>Parameter</th>
<th>Values used in calculation</th>
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<td>kink band width (m)</td>
<td>6000</td>
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Table 3-6. Slip Estimates Using Results of Ross (1988).

<table>
<thead>
<tr>
<th>Right-lateral displacement across kink band</th>
<th>Left-lateral slip on faults within kink band</th>
<th>Error ranges (±7˚)</th>
<th>Parameter</th>
<th>Values used in calculation</th>
</tr>
</thead>
<tbody>
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<td>1126</td>
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<td>573 - 1838</td>
<td>Angle A</td>
<td>136 - 148</td>
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<td></td>
<td></td>
<td>23 – 73</td>
<td>Number of Faults</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>kink band width</td>
<td>4800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>kink band length</td>
<td>5000</td>
</tr>
</tbody>
</table>
Figure 3-1. Regional location map showing: A. The generalized geology and locations of the Mt. Hilgard and other quadrangles in the eastern Sierra Nevada, California. B. The names and locations of a few 15' quadrangles in the eastern Sierra Nevada. C. The lineament analysis of Lockwood and Lydon (1979) of the Marion Peak, Mount Pinchot, Triple divide Peak, and Mount Whitney 15' quadrangles. D. Mount Pinchot 15' quadrangle of Moore (1963). E. The lineament analysis of Lockwood and Lydon (1975) for the Mount Abbot 15' quadrangle. F. The location of the Mt. Hilgard 7.5' topographic quadrangle. The sample locations of Ross (1968) are shown by stars. The Bear Creek kink band of Davies and Pollard (1986) and the eastern Bear Creek kink band, defined in this study, as shown on E and F. The dark circles represent locations of the meter-scale kink bands.
Figure 3-2. The geology of the Mt. Hilgard 7.5' quadrangle from Lockwood and Lydon (1975) overlain on the orthophoto quadrangle. Pluton contacts, shown by thin white lines, are from Lockwood and Lydon (1975). The edges of the eastern Bear Creek kink band analyzed in this study are shown by the heavy white lines, with the Gemini fault zone being the southern margin. Pluton ages are described in Table 3-1. Explanation: Kqm1 = fine- to medium-grained biotite quartz monzonite. Klef = fine-grained facies of the Lake Edison granodiorite. Klps = porphyritic facies of the Lamark granodiorite. KJcl = granodiorite of Chickenfoot Lake.
Figure 3-3. Lineations (dark straight lines) within the Mt. Hilgard 7.5' quadrangle. Pluton contacts, shown by thin white lines, are from Lockwood and Lydon (1975). Explanation: Kqm1 = fine- to medium-grained biotite quartz monzonite. Klef = fine-grained facies of the Lake Edison granodiorite. Klp = porphyritic facies of the Lamark granodiorite. KJcl = granodiorite of Chickenfoot Lake. The north-south edges of the eastern Bear Creek kink band analyzed in this study are shown by the heavy black lines.
Figure 3-4. Orientation of lineaments within the Mt. Hilgard 7.5’ quadrangle. A. Orientation of lineaments within the Lamark and Turret Peak, Lake Edison, and Mono Creek plutons. B. Orientation of lineaments relative to the eastern Bear Creek kink band. Location diagrams, showing the same geographic area as Figures 3-1 and 3-2, for both analyses are located below the rose diagrams. Rays on rose diagrams indicate azimuth, semicircles represent the percent of the total data, and the red line represents the mean orientation and confidence interval. Black lines and arrow indicate data subgroups used for mean and standard deviation calculations. Yellow lines represent the average pluton margin orientation.
Figure 3-5. Length histograms for lineaments digitized in Figure 3.3. A. Data subdivided by host pluton. Plutons include the Turret Peak and Lamark plutons (top), the Lake Edison pluton (middle), and the Mono Creek pluton (bottom). B. Data subdivided by position relative the eastern Bear Creek kink band. Positions include the northeast limb (top), the inner limb (middle), and the southwestern limb (bottom).
Figure 3-6. Theoretical right-lateral monoclinal kink-band model. Modified from Srivastava et al. (1998).

Explanation

\( D \) = the magnitude of right-lateral displacement across the kink band
\( d \) = the magnitude of left-lateral slip on faults within the kink band
\( W \) = kink band width
\( A \) = angle between the inner and outer kink band limbs
\( L \) = the width of the kink band measure normal to the inner limb
\( S \) = the spacing of left-lateral strike-slip faults within the kink band
\( \phi \) = angle between the fold axis and the outer foliation
\( \phi_k \) = angle between fold axis and inner limb of kink band
\( \psi \) = the angle between the outer limb and the inner limb
\( \sigma_1 \) = the direction of the maximum principle stress
\( \beta \) = the angle between the maximum principle stress and the outer limb
\( \Phi \) = the angle between the maximum principle stress and the fold axis

\( W \) = kink band width
\( S \) = the spacing of left-lateral strike-slip faults within the kink band
\( d \) = the magnitude of left-lateral slip on faults within the kink band
\( A \) = angle between the inner and outer kink band limbs
\( L \) = the width of the kink band measure normal to the inner limb
\( S \) = the spacing of left-lateral strike-slip faults within the kink band
\( \phi \) = angle between the fold axis and the outer foliation
\( \phi_k \) = angle between fold axis and inner limb of kink band
\( \psi \) = the angle between the outer limb and the inner limb
\( \sigma_1 \) = the direction of the maximum principle stress
\( \beta \) = the angle between the maximum principle stress and the outer limb
\( \Phi \) = the angle between the maximum principle stress and the fold axis

Explanation

$\phi_k$ = angle between fold axis and inner limb of kink band

$\phi$ = angle between the fold axis and the outer foliation

$\psi$ = the angle between the outer limb and the inner limb
Figure 3-8. Outcrop trace maps, simplified traces, and simplified kink-band models for Mt. Hilgard lineaments, the Hilgard Branch outcrop of Martel (1999) and the Trail Fork and Kip Camp outcrop of Davies and Pollard (1986). See Fig. 3-1 for outcrop locations.
Figure 3-9. Paleostress analysis for the kinked lineaments with the Mt. Hilgard quadrangle, the Hilgard Branch outcrop of Martel (1999), and the Trail Fork and Kip Camp outcrops of Davies and Pollard (1986). Most of the data required projection onto the paleostress line. For the lineaments within the Mt. Hilgard quadrangle, three data points project onto the paleostress line and eight do not.
Figure 3-10. A. Error sensitivities for right- and left-lateral displacement estimates by varying the angle $A$, which is the angle between the inner and outerlimbs of the kink band (see Figure 3-6). B. Error sensitivities calculated by varying the number of faults within the kink band. The end-member situation described in the text is shown by the inset plot. C. Error sensitivities to kink band length and width. For all plots, the maximum and minimum slip estimations for right-lateral displacement across the kink band and left-lateral slip on faults within the kink band are read from the y-axes by laterally projecting the intersection of the grey boxes with the curves, as shown by the heavy arrows. For plot C, the dark grey box corresponds to the magnitude of left-lateral slip and the light grey box corresponds to the magnitude of right-lateral slip.
Figure 3-11. Thermo-mechanical modeling of the Lake Edison pluton by Bergbauer and Martel (1999). Heavy ticks represent their predicted joint orientation and the thin lines represent the observed joint orientations. Except in the thin "neck" of the pluton, the model broadly reproduces the observed lineament orientations.
Figure 3-12. Rotation of the kink band interlimb lineaments using the $13.4 \pm 7^\circ$ constraint of Ross (1988). The lineaments within the western Bear Creek kink band strike $020^\circ$ (Ross, 1988) and this study shows that the northeast outer limb of the eastern Bear Creek kink band strikes $\sim 030^\circ$. The observed lineament strike within the the kink band is $\sim 075^\circ$ (dark line). By applying the $13.4 \pm 7^\circ$ constraint of Ross (1988), the joints within the inner limb of the kink band had an original strike of $062 \pm 7^\circ$ (light grey line and margins of error shown by dashed lines). This magnitude of kinking would cause 1126 m of right-lateral displacement across the kink band and 45 m of left-lateral slip on faults within the kink band. Including the errors of margin, the right-lateral displacement could range from 573 - 1838 m and the left-lateral displacement range of 23 - 73 m.
Figure 3-13. Cartoon of selected plutons of the central Sierra Nevada, California. Crystallization ages from Evernden and Kistler, 1970; Stern et al., 1981; Tobisch et al., 1995. The Sierra Crest shear zone system is composed of the Gem Lake, the Rosy Finch, and the Proto Kern Canyon shear zones. The white surrounding the selected plutons represents older plutons and/or other metamorphic rocks.
**Figure 3-14.** Depiction of the progressive deformation within the Mt. Hilgard quadrangle ~ 91 - 85 Ma. See text for age references. **T0:** The Lamark granodiorite is emplaced ~ 91 Ma. **T1:** Joints open parallel to the maximum horizontal compressive stress (~ 020°). **T2:** The Lake Edison granodiorite is emplaced at ~ 88 Ma. **T3:** Cooling joints in the Lake Edison granodiorite open ~ 062°. **T4:** Mono Creek quartz monzonite is emplaced at ~ 85 Ma. **T5:** As the Mono Creek pluton cools, the Rosy Finch shear zone becomes inactive. **T6:** During cooling, joints in the Mono Creek open ~ 030°. **T7:** The joints become right-laterally kinked in the thermally weakened area of the Rosy Finch shear zone. **T8:** Right-lateral kinking results in the formation of left-lateral strike-slip fault zones at ~ 79 Ma.
CHAPTER 4
CONCLUSIONS

Our analyses of the Gemini fault zone and the regional structures within the Mount Hilgard 7.5' quadrangle show that the Late Cretaceous (~ 91 - 79 Ma) Sierra Nevada magmatic arc was characterized by complex, short-lived deformation events that generated a right-lateral shear zone, cooling joints, a 5-km wide kink band, and various scales of left-lateral strike slip faults. Kink-band modeling shows that a km-scale right-lateral kink band with vertical fold axes and northwest-striking axial planes is a plausible mechanism for the formation of the left-lateral strike-slip faults in the study area. The model provides a coherent explanation for all of the structural elements in the quadrangle. If the geometry of the kinked lineaments resulted solely from kinking, the kink band could have accommodated 1.6 to 5.6 km of right lateral displacement across the kink band and 47 to 951 m of left-lateral slip on each strike-slip fault within the kink band. When constrained by independent paleomagnetic data from Ross (1988) and the modeling of Bergbauer and Martel (1999), the model indicates that reasonable magnitudes of left lateral slip, approximately 44 m, on faults within the kink band can be generated through 1.1 km of right-lateral kinking. These data coincide with the 45 m of average left-lateral slip on the Gemini fault zone.

The structural analyses of the Gemini fault zone show that the fault zone is composed of steeply dipping, northeast- and southwest-striking fault planes that have mineral lineations that dominantly plunge gently to the southwest. The slip-distribution divides the fault zone into three segments with trace lengths of ~ 2.5 to 3 km. Orientation analysis of joint and fault surfaces indicates that the fault zone parallels the joints in the Lake Edison and Mono Creek plutons, and suggests that, at least in part, the joints control the fault zone geometry. The slip-distance data show that local slip minima are segment
boundaries, the steepest slip gradient occurs at the western third of the fault zone, and that slip tapers to zero near the fault zone’s eastern and western termination. This suggests that the fault zone may have initiated in the Lamark pluton, the oldest pluton that the Gemini fault zone cuts, and propagated to the east. Slickenline orientations vary nonsystematically over the entire fault zone and segment boundaries and may reflect the fault zone’s complex geometry and resulting stress heterogeneities. Microstructural data indicate that deformation occurred at and below lower greenschist facies conditions on narrow, brecciated slip surfaces. The cataclastic and brecciated textures appear to be slip invariant where slip magnitudes are greater than 35 m. Veins and masses of sericite overprint the breccia and cataclasite, indicating that the dominant period of mineralization occurred after faulting and that the fault zone was hydraulically connected during mineralization.

Taken together, the 10-km scale, left-lateral Gemini fault zone and the km-scale eastern Bear Creek kink band elucidate late-stage structural components of the Late Cretaceous Sierra Nevada transpressional magmatic arc. The occurrence of the kink band and the left-lateral faults, active within 6 Ma of the emplacement of the Mono Creek pluton and dominated by brittle behavior, indicate that the area was characterized by steep thermal gradients that allowed transient deformational events, recorded in the Lamark, Lake Edison, and Mono Creek plutons. The brittle structures described here may have locally accommodated between 1.7 and 4.8 km of transcurrent motion during the waning stages of magmatism. If similar structures exist in conjunction with the two other right-lateral shear zones found in the eastern Sierra Nevada (i.e., the Gem Lake shear zone of Greene and Schweickert, 1995 and the Proto Kern Canyon fault zone of Busby-Spera and Saleeby, 1990), the kinked structures could account for 4.8 to 16.8 km of late-stage, right-lateral deformation.
REFERENCES


Lockwood, J. P., and Moore, J. G., 1979. Regional deformation of the Sierra Nevada,
California, on conjugate microfault sets. Journal of Geophysical Research 84, 6041-6049.


