THREE-DIMENSIONAL STRUCTURE OF SMALL STRIKE-SLIP FAULT ZONES IN GRANITIC ROCK: IMPLICATIONS FOR FAULT-GROWTH MODELS

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Geology

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1998
ABSTRACT

Three-Dimensional Structure of Small Strike-Slip Fault Zones in Granitic Rock: Implications for Fault-Growth Models

by

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Utah State University, 1998

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Three small strike-slip fault zones exposed in granitic rock in the central Sierra Nevada, California, provide field-based data to construct three-dimensional representations of each fault zone in order to compare with the geometries predicted by existing fault-growth models. All three fault zones are nearly vertical, strike N60°E, and have left-lateral slip. The fault zones range from 60 to 140 m in length and 1 to 12 m wide. Each fault zone consists primarily of parallel to subparallel fracture and fault traces 2 to 56 m long and is separated 25 cm to 7 m by intact rock. One fault zone contains two simple fault zones that consist of fractured rock separated from relatively unfractured rock by two nearly parallel boundary faults. Fracture and fault trace characteristics are a function of fault zone development and complexity. Traces interconnect primarily by way of junctions and steps, with traces branching away from each other at junctions having angles between 10° to 80° whereas steps branch away at angles between 10° to 40°. Faults terminating as a splay or horsetail splay are rare. Splay fractures strike away from the fault traces at angles of 10° to 60°.

Individual faults and the fault zones have irregular displacement-length
profiles. Episodic brittle fracturing, hydrothermal mineralization, and alteration are pervasive along fractures and faults. Thickness, composition, and location of hydrothermal mineralization and alteration along fault traces show no consistent pattern and indicate a brittle strain softening process occurred. The widespread distribution of chlorite-epidote mineralization suggests that each fault zone acts as a through-going passageway for fluids.

Fault-growth models involving the in-plane propagation of shear displacement along faults and having strain as the boundary condition match the field data the best. All three fault zones resemble those fault-growth models in which fault zone development is a nonuniform process with the growth of individual fractures and faults affecting the nucleation, propagation, and geometry of subsequent fractures and faults. Three-dimensional representation of these fault zones will constrain spatial statistical and stochastic modeling of fault zone nucleation and propagation.
ACKNOWLEDGMENTS

First, I would like to thank my advisor, James P. Evans. Jim provided support and encouragement throughout the long process of coursework, research, fieldwork, and writing the thesis. He was always willing to listen to my ideas, frustrations, and problems associated with the project and life in general. Jim’s enthusiasm for geology, his seemingly never-ending “brain-sparks,” and warped sense of humor are infectious and helped me through the process of writing this thesis. There is no better graduate advisor at this university.

Research for this thesis was made possible by a grant from the U.S. Department of Energy Office of Basic Energy Science (Grant # DE-FG03-95ER14526) awarded to Dr. J. P. Evans.

My committee members, Susanne Janecke and Kevin Hestir, provided guidance on how to approach my project, what to focus on, and helped me organize my thesis into a readable document. I would like to thank the faculty and staff at the Geology Department of Utah State University for their support and encouragement. They are the reason why this department is the great place it is. I would also like to thank Amy Hochberg and Torrey Copfer for being my field assistants. I would especially like to thank Torrey for bringing lots of aspirin into the field. Thanks also to Vince Jefferies, who cut and prepared my rock samples for thin-sectioning, and to John Greg Solum, who did the x-ray diffraction analysis.

I would have never completed this work without the support and friendship of many people. Special thanks to my officemates: Steve Schulz, Colby VanDenburg, Kelly Keighley, Jim Blankenau, Siang-Joo “Jonathan” Lim, and K. Jill Hammond, who provided encouragement, stimulating conversations, and a lot of mirth, mayhem, and madness. Without the support of my far-away friends, Stefanie
and Ben Larson, Jo Stanley, Della Snyder, Melissa Markell, Sunny Steinmeyer, and Joan Fryxell, I would have cracked a long time ago. My heartfelt appreciation especially goes out to Stef and her mom, Shirley Vieths, who were always willing to put me up whenever I just had to get out of Utah for a while.

Most of all, I would like to thank Michael, Jackie, and Ani Matosian, otherwise known as Dad, Mom, and Evil Kid Sister. Their love, encouragement, support, and temptations to come home have kept me going when nothing else could. They put up with my long-distance phone calls and email messages. They always believed in me even when it seemed like I was never going to finish. They never minded when I showed up at the front door after escaping from behind the Zion Curtain. Better people cannot be found in this world, and I consider it an honor that they have accepted me into their family.

To all the others who deserve my appreciation, but are too numerous to list individually, I thank you all.

Kim Robeson

Note: This thesis was approved by the graduate college on November 18, 1998. On November 22, 1998, Kim Robeson died. Plates 1, 2, 3, and 4 were completed at the time of his death; Plate 2 needed minor revisions, and Plate 2 in this thesis is Kim’s version without revisions.

It was privilege to have worked with Kim.

James P. Evans
December 3, 1998
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INTRODUCTION

How fault zones nucleate and propagate in rocks of all types and at all scales is important to understanding subsurface fluid flow, earthquake mechanisms, and processes of crustal deformation. Faults act as conduits for groundwater flow and influence the migration, trapping, and production of hydrocarbons. Furthermore, the extraction of geothermal fluids and some economic minerals is influenced by fault location and geometry. Fluid pressure and fluid-assisted mechanisms may be critical in weakening earthquake-generating faults, thereby increasing the risk of seismic events along a fault zone. More importantly, faults act as a guide for the shear displacement which occurs during an earthquake. Because brittle deformation of the lithosphere is accomplished by faulting, how faults nucleate and propagate becomes important for understanding the mechanics of lithospheric deformation.

Our current understanding of the mechanics of fault nucleation and growth comes primarily from laboratory experimental data (Lawn and Wilshaw, 1975; Broek, 1986; Cox and Scholz, 1988; Reches and Lockner, 1994; Moore and Lockner, 1995), analog modeling (Smith and Durney, 1992; Schreurs, 1994; An and Sammis, 1996), and theoretical studies (Martel and Pollard, 1989; Cowie and Scholz, 1992a, 1992b), supplemented by field investigations (Segall and Pollard, 1983b; Martel et al., 1988; Martel, 1990; Scholz et al., 1993; Dawers et al., 1993; Dawers and Anders, 1995). While laboratory experiments and analog modeling are useful in establishing physical processes and in validating theories, many features of faults and fault zones observed in the field have not been reproduced in these experiments. Perhaps the results of these experiments do not resemble field observations because these experiments are conducted in controlled environments, and the homogeneity of the material used, the limited sample size, or the applied boundary conditions do not reflect real-world conditions. Characteristically,
laboratory experiments and analog modeling only investigate the mechanics of faulting in a plane perpendicular to the fault (i.e., in two dimensions). Likewise, theoretical models describing the mechanics of fault and fault zone nucleation and growth based on field studies of existing faults commonly consider only the two-dimensional geometry of the fault zone.

Faults are three-dimensional features. As such, the three-dimensional structure of faults and fault zones may influence how earthquake ruptures propagate through the earth and the hydrological behavior within fault zones. Therefore, to understand the real-world mechanics of fault morphology and how fluid travels through a fault zone, it is necessary to study the structure of a fault zone in three dimensions.

Only recently have field-based investigations of the three-dimensional structure of, and slip distribution along, faults and fault zones been undertaken. Normal faults have been studied by Barnett et al. (1987), Walsh and Watterson (1987, 1988), Childs et al. (1993), Nicol et al. (1996), and Willems (1997). Strike-slip faults have been examined by Christiansen (1994), Evans et al. (1996), Martel and Evans (1996), Lim and Evans (1997), Robeson and Evans (1997), and Martel and Boger (1998). This study also focuses on the three-dimensional structure of faults and fault zones in real-world situations. Specifically, this study provides: (1) detailed field-based information about the geometry of small fault zones; (2) field data documenting the distribution, orientation, density, interactions between, and cross-cutting relationships of fractures, faults, and dikes within each fault zone; and (3) detailed descriptions of the geology and mineralogy of fractures and faults within the fault zones.

This study has two major goals. First, detailed field-based information will be used to construct computer-generated three-dimensional representations of the
fault zones. These three-dimensional representations, along with the other geologic data collected, will be used to constrain spatial statistical and stochastic modeling of how faults and fault zones nucleate and propagate in three dimensions (Hestir and Martel, 1996; Hestir et al., unpublished data). Second, the field data will be used to compare real-world field observations with the predictions of current models of fault growth. Thus this study provides data that can be used to both construct and constrain a new fault-growth model, and to compare with existing fault-growth models.

This study focuses on small faults and fault zones. The majority of research on fault geometry and fault-growth models has investigated faults at the microscopic scale or kilometer to tens of kilometers scale. Small faults and fault zones are often considered to be a minor element of a larger fault zone (Gillespie et al., 1992). As a result, this intermediate scale of fault and fault zone development is often overlooked. But it is at this intermediate scale that individual faults coalesce to form larger fault zones. Faults at the intermediate scale commonly retain outcrop-scale evidence for their nucleation and growth. Furthermore, fluid-rock interaction that may have profound effects on later fault properties and behavior tend to develop within fault zones at this intermediate scale. Thus an important stage in fault and fault zone nucleation and growth has not been considered by previous investigations.

Fieldwork for this study was conducted in the central Sierra Nevada batholith of California. Uplift of the batholith and subsequent glaciation provide excellent exposures of the faults and fault zones. Most faults and fault zones, even small ones, are rarely contained within a uniform rock type (Gillespie et al., 1992). The fault zones investigated for this study are completely contained within the Lake Edison Granodiorite, thereby providing information about fault zones not only in a uniform rock type, but also in rock material that is more representative of real-world
conditions than the fine-grained isotopic rock used in laboratory experiments. Furthermore, problems associated with investigating faults or fault zones in multiple rock types are eliminated. Previous investigations conducted in this area of the Sierra Nevada batholith have focused on joint formation, as well as fault development and growth in two dimensions (e.g., Segall and Pollard, 1983a, 1983b; Martel et al., 1988; Martel, 1990; Bürgmann and Pollard, 1994; Christiansen and Pollard, 1997).

One of the goals of this study is to compare real-world observations with the predicted results of current theoretical fault-growth models. There are two major fault-growth models: the fracture linkage model of Segall and Pollard (1983b), Martel et al. (1988), Martel and Pollard (1989), and Martel (1990); and the process zone model of Cox and Scholz (1988), Scholz (1990), and Cowie and Scholz (1992a). Supplementing these two models are the shear experiment models of Schreurs (1994) and An and Sammis (1996). These models, as well as complementing investigations, are described and discussed in the Comparison section.

This study is divided into eight sections. The first describes the geologic setting of the study site. Following this is a terminology section. Next is a description of the methodologies used, both in the field and in the laboratory. Then a detailed description of the fault zones investigated for this study is given. A discussion of the three-dimensional representation of the collected field data is followed by a section in which the field data are compared to the predictions of previous models of fault nucleation and growth. Next, the implications of my field observations, as well as the observations of other studies, on current fault-growth models are presented. This thesis concludes with suggestions for future fault-growth modeling.
The study area is in the Mount Abbot 15-minute quadrangle of the central Sierra Nevada, California, and was first mapped and described by Lockwood and Lydon (1975). Field research for this study was conducted in the Bear Creek region of the quadrangle, southeast of Lake Edison (Fig. 1). The Bear Creek region has the typical "U" shape of glacially carved canyons in the Sierra Nevada. The flat tops of the mountain peaks surrounding the canyon are remnants of the gently undulating erosional surface produced across the Sierra Nevada prior to about 10 m.y. ago (Lockwood and Lydon, 1975). On the mountainsides are rugged cirques and talus deposits. Alpine and subalpine meadows are present in the flatter portions of the valley (Lockwood and Lydon, 1975). Glacial striations are widespread over the exposed plutonic rocks. Overall, modification of the glacially sculptured topography has been minor (Lockwood and Lydon, 1975).

More importantly for the purpose of this study, the Bear Creek area contains a pervasive system of northeast-trending fractures and faults, ranging from ~1 to 8 km in length, first recognized by Lockwood and Lydon (1975, Fig. 2). Preferential erosion occurred along these fractures throughout the area, and as a result, they are prominent features commonly marked by linear stream channels, long deep trenches, or parallel lines of trees and shrubs which cross otherwise barren rock (Fig. 2) (Lockwood and Lydon, 1975). Finally, the presence of topographic relief in the Bear Creek region makes this portion of the Mount Abbot quadrangle well suited for investigating the three-dimensional structure of faults and fault zones in granitic rock.

The Bear Creek area is situated in the Lake Edison Granodiorite, a northwest-trending pluton that is more than 50 km long (Lockwood and Lydon,
Figure 1. Geologic map of the Bear Creek region of the Mount Abbot quadrangle and the locations of the three fault zones investigated in this study. Trail is the Pacific Crest/John Muir hiking trail. BCFZ= Bear Creek Fault Zone, JRFZ= Jim's Ridge Fault Zone, KJd= undifferentiated mafic rock, Kl= Lamarck Granodiorite, Kle= Lake Edison Granodiorite, Klef= fine-grained facies of the Lake Edison Granodiorite, Klep= porphyritic hornblende granodiorite facies of the Lake Edison Granodiorite, Kmc= Mono Creek Granite, LCFZ= Lower Camp Fault Zone, mz2= area of extensive quartz-epidote-chlorite mineralization, Qt= undifferentiated Quaternary deposits. Modified from Lockwood and Lydon (1975).
Figure 2. Air photo of study area. Dark northeast-trending lineaments are fault zones crossing the John Muir Intrusive Suite. BCFZ= Bear Creek Fault Zone, JRFZ= Jim's Ridge Fault Zone, LCFZ= Lower Camp Fault Zone. USDA air photo, project no. S1-11, flight no. 06019-11-76, taken on 7-2-76.
The Lake Edison Granodiorite is a fine- to medium-grained, equigranular biotite-hornblende rock with abundant titanite (Lockwood and Lydon, 1975; Bateman, 1992). In places where this pluton is unfractured, the rock composition is relatively uniform and lacks fabric associated with emplacement of the pluton. Therefore, structural features and mineral alteration found in the study area are likely to be the result of faulting and hydrothermal alteration processes and not the result of primary igneous processes. Previous studies by Segall et al. (1990) have shown that the fractures and faults commonly contain a different mineral assemblage than the host granodiorite. Segall et al. (1990) documented that joints are mineralized to a lower greenschist assemblage containing epidote, chlorite, biotite ± sphene ± calcite ± zeolites, and that faults contain the same minerals plus abundant quartz. The presence of lower greenschist and quartz mineralization indicates that the faults were active hydrologic conduits and can be used to estimate the amount of hydrologic connectivity within a fault zone (Evans et al., 1996).

The Lake Edison Granodiorite is one of three plutons that make up the John Muir Intrusive Suite within the Mount Abbot quadrangle (Bateman, 1992). The westernmost pluton is the Lamarck Granodiorite, the central pluton is the Lake Edison Granodiorite, and the easternmost pluton is the quartz monzonite of Mono Recesses (herein called the Mono Creek Granite after Bateman [1992]). Field relations show that the Lake Edison Granodiorite intrudes the Lamarck Granodiorite and is intruded by the Mono Creek Granite (Bateman, 1992), indicating that the Lamarck Granodiorite is the oldest pluton and the Mono Creek Granite is the youngest. Radiometric dating of the Lake Edison Granodiorite gives a concordant U-Pb zircon ages of 90 Ma (Stern et al., 1981) and 88 ± 1 Ma (Tobisch et al., 1995), two K-Ar biotite ages of 82 and 77 Ma, and one hornblende age of 85 Ma (Kistler et al., 1965; Evernden and Kistler, 1970). Because the Lamarck Granodiorite has a
discordant U-Pb zircon age of 90 Ma (Stern et al., 1981), K-Ar hornblende ages of 90 and 86 Ma, and biotite ages of 85 and 79 Ma (Kistler et al., 1965; Evernden and Kistler, 1970), the Lake Edison Granodiorite is apparently only slightly younger than the Lamarck Granodiorite (Bateman, 1992).

Determination of the time of fracturing within the Bear Creek area is based on both field relationships and geochemical analysis. Whereas the fractures clearly formed after the host granodiorite had cooled sufficiently to form joints, the scarcity of overlying Cenozoic rocks has made it difficult to further constrain this age based solely on field observation (Segall et al., 1990). Field relations led Segall and Pollard (1983a) to suggest that the fractures initially formed as dilational fractures (i.e., joints) at depths of at least several hundreds of meters or more. Furthermore, Segall and Pollard (1983a) calculated that these dilational fractures developed when subjected to relative tensile stresses (average remote stress plus internal fluid pressure) of approximately 1 MPa to 40 MPa. Some of the faults in the Bear Creek area contain secondary muscovite grains which formed as a product of hydrothermal alteration. From \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of these muscovite grains, Segall et al. (1990) concluded that the faults in the Bear Creek area formed between 75 and 79 Ma. This age determination suggests that fracturing occurred within a relatively short time interval following emplacement of the host granodiorite.

The specific emplacement depth of the Lake Edison Granodiorite has not been established. Nevertheless, comparison of mineralogic and whole rock compositional data from the nearby and nearly contemporaneous Red Lake and Eagle Peak plutons indicates an emplacement pressure of approximately 100 MPa, suggesting an approximate emplacement depth of 4 km (Noyes et al., 1983). Furthermore, geobarometers from the central portion of the Sierra Nevada batholith indicate pressures in the general range of 100 to 200 MPa, equivalent to the
overburden weight of 3.5 to 7 km of rock (Bateman, 1992).

Following emplacement, uplift and exposure of the Sierra Nevada batholith began during the Late Cretaceous (Miller et al., 1992). At about 80 Ma, magmatism ceased in the central Sierra Nevada (Cowan and Bruhn, 1992). Rapid uplifting of the batholith occurred during the Late Cretaceous, presumably due to isostatic compensation as erosion removed the overlying roof pendant (Miller et al., 1992). Clasts of granite from the batholith were deposited westward into the adjoining fore-arc continental borderland (now the Central Valley of California) during latest Cretaceous and Paleocene time (Miller et al., 1992), suggesting that the uplifting event ended during the Paleocene. Because the plutons of the John Muir Intrusive Suite are not deeply eroded, the surface exposure of these plutons indicates a proximity to the tops of the intrusions (Bateman, 1992). This lack of substantial erosion has led Bateman (1992) to suggest that the Lake Edison Granodiorite was exposed towards the end of the Late Cretaceous uplifting event.

After exposure, the Sierra Nevada batholith was eroded to a low relief by Eocene time (Bateman, 1992). Uplifting and the westward tilting that accounts for the present configuration and height of the Sierra Nevada began about 25 Ma, but two-thirds of the uplift has taken place during the last 10 m.y. (Huber, 1981). This continuing deformation is related to late Cenozoic extension and deformation along the western margin of the Basin and Range province (Bateman, 1992). During Pleistocene time, extensive glaciers repeatedly formed and retreated throughout the Sierra Nevada, carving the glacially sculptured topography characteristic of the region (Lockwood and Lydon, 1975).

The Bear Creek portion of the Lake Edison Granodiorite contains several features extremely suitable for investigating fault systems. The pluton contains widespread exposures of aplite dikes that range from centimeters to meters in width,
and extend for tens of meters in length. Whereas these dikes have a range of orientations, most have steep dips. Dike offsets along a fault trace permits determination of the net slip along a fault, from which the slip gradients can be calculated. These data can then be used to study the effects of increasing slip amounts on fault zone structures. In addition to aplite dikes, mafic inclusions ranging from centimeters to tens of centimeters in size exist throughout the study area, but are not as common as the dikes. These inclusions are also used for fault slip analysis. Another feature is the uniform sense of offset along the faults in this area. Field investigations by Segall and Pollard (1983b), Martel et al. (1988), and Martel (1990) established that left-lateral offset is the dominate sense of movement along faults seen in the study area. This study confirms that right-lateral offsets were either absent or were restricted to secondary fault processes. This feature eliminates the need to consider multiple offset directions on a fault trace over time. In addition, the effects of subsequent deformation associated with uplifting of the pluton and glaciation are minimal (Martel, 1990), thereby allowing for investigation of faulting processes during a single deformation event.

Previous investigations in the Bear Creek region of the Mount Abbot quadrangle involve the description and the mechanical analysis of fault nucleation and growth in granitic rocks in two dimensions. Segall and Pollard (1983b) used three-dimensional plan views of outcrops in this area to formulate a two-dimensional model for strike-slip fault development. Martel et al. (1988) and Martel (1990) studied plan views of outcrops in this area to investigate the development of simple and complex fault zones. This study differs from these previous investigations in that the three-dimensional structure of fractures and fault zones is emphasized to obtain field data that will be compared to theoretical models concerned with the nucleation and propagation of faults and fault zones.
TERMINOLOGY

Structures resulting from brittle deformation have distinctive forms due to the mechanics of brittle fracturing (Scholz, 1990). Over the years, geologists have introduced a broad nomenclature to describe both the geometry and the mechanical processes associated with joints, fractures, and faults. Unfortunately these terms are usually incomplete, not rigorously defined, or improperly used, leading to confusion in the geological literature. To reduce confusion and to establish a consistency in terminology, the definitions and descriptions of terms to describe brittle deformation used in this study are provided below. The terminology used in this study is consistent with the usage of fracture mechanics terminology as applied by Segall and Pollard (1980, 1983a, 1983b, 1987), Martel and Pollard (1989), and Martel (1990, 1997).

Fractures are surfaces along which rocks or minerals have loss continuity and, therefore, strength. Descriptive terms used to characterize fractures at the outcrop scale include joints, fractures, and faults; each of which may have a different interpretation for each investigator. In this study, fracture is a general term used to describe a discontinuity along a rock surface, particularly where there is not clear outcrop-scale evidence for tensile or shear displacement. The term joint is used here to describe a fracture in which there is evidence for displacement dominantly normal to its surface (Pollard and Aydin, 1988). In contrast, the term fault is used to describe a fracture in which there is clear outcrop-scale evidence of shear displacement across its surface (Martel, 1990). Field evidence for joints and faults includes displaced markers, surface textures, mineral precipitates, and altered rock surrounding the fractures (Segall and Pollard, 1983a; Pollard and Aydin, 1988). Finally, the line representing the intersection of a fracture, joint, or fault surface with
the rock surface is called the fracture, joint, or fault *trace*.

Brittle deformation is distinguished by the relative motion that has occurred across the fracture trace during formation. Following the nomenclature used in fracture mechanics (Lawn and Wilshaw, 1975), the displacement motion, or the growth direction of a fracture, can be categorized into three modes (Fig. 3). Mode I is a tensile, or opening, fracture in which the displacement is normal to the fracture trace. Mode II, or in-plane shear, is a fracture in which the displacement is in the plane of the fracture and normal to the tip of the fracture. Mode III, or antiplane shear, is a fracture in which displacement occurs in the plane of the fracture and parallel to the fracture tip. A mixed mode fracture is a combination of Mode I with Mode II or Mode III displacement or a combination of just Mode II and Mode III displacement (Scholz, 1990; Twiss and Moores, 1992).

The geometric and mechanical definitions given above all describe fractures, yet each is based on different criteria. The geometric terms result from field observation of fracture patterns on rock surfaces, whereas the displacement mode terms are used to describe the mechanics of fracture development. Joints are associated with Mode I displacement whereas faults are associated with the shearing modes: Mode II and Mode III (Pollard and Aydin, 1988). However, the displacement may vary along a fracture trace, thereby involving a mixture of Modes I, II, and III (Fig. 4) (Pollard and Aydin, 1988). In this study, only the geometric descriptions will

![Figure 3. The three fracture propagation modes (e.g., Broek, 1986). (a) Mode I. (b) Mode II. (c) Mode III.](image-url)
Figure 4. Drawing of a fracture trace with a mixture of Mode I, II, and III displacement. Mode I displacement is represented by the small ellipses parallel to $\sigma_2$ and along the edge of the fracture surface. Mode II displacement occurs in the plane of the fracture surface. Mode III displacement is represented by the curved surfaces at the tips of the fracture, normal to the fracture surface. From Scholz (1990).
be used to describe the fracture geometry observed in the field. Both the
geometric and mechanical terms will be used in the Comparison and Discussion
sections.

Individual fracture traces have finite lengths. The point at which the fracture
trace terminates on the surface of the rock is called the fracture tip (Twiss and
Moores, 1992). Fractures terminate in several ways. They may simply die out at
their tip (Fig. 5a) or terminate as a set of splay fractures, which are smaller
subsidiary fractures that branch off from the main fault and die out either at a tip or
intersect another fracture trace (Fig. 5b) (Segall and Pollard, 1983a). If such splays
show evidence of shear displacement, they are referred to in this study as splay
faults. Multiple splay fractures that branch off from the main fault at fairly regular
intervals, have comparable geometries, and curve toward the receding fault block
form a horsetail splay (Fig. 5c) (Granier, 1985). Joints do not terminate in a splay
structure, but may curve and terminate as an intersection with another joint (Pollard
and Aydin, 1988). Finally, fractures may terminate by intersecting with another
fracture trace.

Fractures commonly divide into two or more fracture traces, one of which
may have the same orientation as the original fracture. The fracture that trends at a
different orientation is referred to here as the branch fracture. The point where a
branch fracture intersects another fracture trace is called a fracture junction. Splay

![Figure 5](image)

**Figure 5.** Styles that a fault trace might terminate in as discussed in this
study. (a) Dying out at a tip without interaction with another trace. (b) Terminating as a splay fracture. (c) Terminating as a horsetail splay.
fractures may exist within the acute angle between the two separating fractures. A branch fracture that connects two parallel or subparallel, non-coplanar fractures is termed a *transfer fracture* (Fig. 6a). Where two fracture traces intersect one another and continue past the intersection is called a *crossover*. As with junctions, splay fractures may exist at crossovers.

Non-coplanar, but parallel to subparallel fracture traces are commonly joined together by a short fracture oriented obliquely from the tips of the non-coplanar fractures, forming a continuous fracture trace (Fig. 6b). As with Martel (1990), such a feature in this study is called a *step*. In some cases, non-coplanar fault traces may extend past one another with small splay fractures extending from the fault tips and intersecting the parallel fault at a junction, producing a rhomb-shaped structure (Fig. 6c). This structure is referred to here as a *stepover*. Commonly, a large stepover will contain numerous straight and parallel to subparallel transfer fractures between the two fault traces (Fig. 7). Such a feature is called a *fault step complex*. Steps, stepovers, and fault step complexes are described as being either right or left (e.g., a *left step*) based on whether the step is to the right or to the left as one progresses along the fracture trace (Twiss and Moores, 1992). This definition remains independent of the sense of slip along the fault.

The term *fault zone* is commonly used to describe a band of finite width in which there are many parallel or subparallel fractures that may or may not intersect with one another. These fractures are separated from one another by unfractured rock. However, a fault zone may contain a structure that has a tabular volume of fractured rock separated from relatively unfractured rock by two nearly parallel faults called *boundary faults* (Fig. 8a). The rock between the boundary faults contains transfer or splay fractures that do not cross the boundary faults and may be highly brecciated or eroded (Martel, 1990). Such a structure is referred to in this study as a
Figure 6. Types of interconnections between fracture and fault traces discussed in this study. (a) Transfer fracture. (b) Step. (c) Stepover.

Figure 7. Basic structure of a fault step complex. Connecting transfer fractures may be straight or curved. The spacing between transfer fractures is typically nonuniform.

Figure 8. Basic structure of a simple fault zone. (a) Boundary faults, transfer fractures, and splay fractures. Transfer fractures extend across the simple fault zone, but do not cross the boundary faults. Splay fractures branch away from a boundary fault, but do not extend across the simple fault zone. The spacing between the transfer and splay fractures is nonuniform. The rock volume within the simple fault zone is typically brecciated and hydrothermally altered. (b) Steps that link non-coplanar segments of the boundary faults to one another. From Martel and Pollard (1989).
simple fault zone. Simple fault zones are 0.5 to 3 m thick, can be up to 1 km long, and have a maximum strike-slip displacement of about 10 m, of which all of this displacement is concentrated on the boundary faults (Martel et al., 1988; Martel, 1990). The boundary faults defining a simple fault zone consist of straight, non-coplanar fault traces tens of meters long that are linked together by steps (Fig. 8b) (Martel, 1990). The fractured rock within a simple fault zone is typically altered. For the Lake Edison Granodiorite, this alteration is manifested by chlorite, epidote, and sphene replacing hornblende, epidote and mica replacing the feldspars, and chlorite replacing biotite (Segall et al., 1990).
METHODOLOGY

Three different fault zones of varying complexity and development were investigated (Fig. 1): the Bear Camp Fault Zone (BCFZ), which extends over a 2890 m high ridge; the Lower Camp Fault Zone (LCFZ), which is located in a bowl-shaped area north of the BCFZ; and the Jim's Ridge Fault Zone (JRFZ), located along a 2900 m high ridge on the west side of Bear Creek, 1.2 km northwest of the BCFZ. The BCFZ consists of two simple fault zones surrounded by numerous parallel to subparallel fracture and fault traces. The fault zone extends over an area with topographic relief, providing excellent exposure for obtaining three-dimensional measurements of the fractures and faults that comprise the zone. The presence of offset dikes allows the distribution of the net slip on faults within the fault zone to be investigated. This fault zone has developed to a stage such that a substantial amount of field data pertaining to the geometry of the fractures and faults comprising the fault zone could be collected.

The LCFZ is a smaller, less complex, fault zone than BCFZ. Importantly, the LCFZ does not contain any simple fault zones. Instead, this fault zone contains several faults which appear to coalesce along the length of the fault zone, only to terminate against a rubble zone which may represent a slightly developed simple fault zone. As with the BCFZ, numerous offset markers such as dikes and inclusions are present. Thus net slip analysis can also be done for this fault zone. Being located in a bowl-shaped area, there is sufficient topographical relief for obtaining three-dimensional data of the fault zone.

The JRFZ contains a primary fault trace with a second fault trace forming a crossover approximately halfway along the primary fault trace. In this fault zone, it is the presence of a stepover exposed in three dimensions along the primary fault
trace that is of interest. As with the other two fault zones, the JRFZ contains offset dikes which are located at both ends of the fault zone trace.

Field Methods

Field work entailed mapping the traces of the three fault zones in order to obtain data necessary to construct a three-dimensional representation of each fault zone. In short, this field work involved establishing fixed control points from which the polar coordinates of individual points along the fault zone are determined. Field calculations involved calculating the map distance and elevation of the measured points. Further work involved locating other geologic features on the field map, recording attitudes taken along fracture and fault traces, obtaining rock samples, and creating detailed maps of important geological features too small or too detailed to be represented on the field maps. What follows below is a detailed description of the field procedure.

The first step in mapping a fault zone involved establishing the control and map points from which measurements were to be taken. Each point measured in the field has an alphanumeric designation, starting with a letter representing the day and a number representing a point on the ground from which the measurement was taken (e.g., B20). A primary control point to which all measurements will be referred was selected first. The control point is A0 for the BCFZ, K0 for the LCFZ, and CP for the JRFZ. Each of these control points was arbitrarily located, usually at one end of the fault zone. None of the primary control points were located on a fracture or fault trace. The primary control point was assigned a field map coordinate of (0,0), from which all subsequent points were measured. Furthermore, each of the primary control points was assigned an elevation of zero, regardless of the point’s actual elevation. Secondary control points were necessary along each fault zone because length and topography prevent direct measurement of the entire fault zone from the
primary control point. These secondary control points were measured from the primary control point and then subsequent map points were measured from the secondary control point. Unlike the primary control point, the secondary control points may be located on a fracture or fault trace.

Map points were established where some feature of importance to the study of the fault zone was located. All the map points were located on a fracture or fault trace. Locations where dikes come in contact with individual fracture or fault traces were chosen as map points. Fracture and fault termination points, whether at a splay or a tip, were also locations for map points. The point where a fracture or fault trace disappears beneath, or becomes exposed from, a covered area received a map point designation. Other map points were located at junctions, crossovers, stepovers, and fault step complexes. Changes in topography or trend of a fracture trace also received a map point designation.

Surveying the fault zones involved using three simple devices. A Sonn portable hand-held electronic distance meter (EDM) and receiver was used to measure the distance between the control point and each map point. The bearing of the map point relative to the control point was determined by using a Brunton compass attached to a tripod located directly above the control point. Finally, the angle representing the vertical relief between the control point and the map point was measured using an Abney level.

After a series of measurements, field calculations were performed in order to create a map view of the fault zone. Each map point measurement gives a polar coordinate relative to a control point. The map distance between the control and map point was obtained by using the equation:

\[ md = (\cos \theta)(sd) \]

where \( md \) is the map distance, \( \theta \) is the angle representing the vertical relief, and \( sd \) is
the distance measured with the EDM between the control and map points. Each map point was then located onto the field map using a scale and protractor. The BCFZ and JRFZ were mapped at a scale of 1:200 whereas the LCFZ was mapped at a scale of 1:100.

After the map points were drawn onto the field map, the individual fracture and fault traces were drawn in, connecting the map points together. In addition, intermediate points along fracture traces and subsidiary features within the fault zones were measured using a tape and located onto the field map. The location and trend of the dikes and inclusions were measured and drawn in, as well as the offset along fault traces. Where strike and dip measurements were taken along fracture and fault traces, the attitude and exact location of these measurements were placed on the field map. Finally, the location of rock samples removed for laboratory studies was placed on the field map.

In the field, the attitude, or the relation of a directional feature in a rock to a horizontal plane, of the fracture, fault, and dike traces was recorded using the right-hand method. When using this method, the strike is taken to be the azimuth along which one looks while positioned so that the dip direction is to the right. For an example, a measurement of N40°E, 80°S is recorded as 40°, 80°. In contrast, a measurement of N40°E, 80°N becomes 220°, 80°. This method of representing attitude measurements is used on all the figures and plates. To facilitate the readability of this study, the dip directions also contain a directional indicator. Thus N40°E, 80°S is written as 40°, 80°SE, and N40°E, 80°N is written as 220°, 80°NW.

After the field maps were completed, detailed maps of special features within each fault zone were constructed. Detailed maps were drawn at specific junctions, stepovers, crossovers, and complex zones representing interesting geological processes. Particular attention was paid to stepovers, interconnecting splay fractures,
and mineralization features.

The elevation of each map point relative to the primary control point was calculated in the field at the same time as the field maps were constructed. This permits recognition of any possible error in measurement or calculation that can then be corrected in the field. The calculation of map point elevations involves two equations. If the map point was topographically higher than the control point, then the equation:

\[ \text{elevation} = h + (\sin \theta)(sd) \]  

(2)

was used, where \( h \) is the height of the compass above the control point, \( \theta \) is the vertical relief between the compass and the map point, and \( sd \) is the measured distance between the two points. If the map point was topographically lower than the control point, equation (2) changes to:

\[ \text{elevation} = h - (\sin \theta)(sd). \]  

(3)

As secondary control points were established, the elevation of the secondary control point was calculated relative to the primary control point. The map point elevations determined from secondary control points were then added or subtracted from the primary control point elevation, so that all elevations calculated in the field are relative only to the primary control point.

Twenty-two rock samples were collected from within the BCFZ and one sample was collected from within the LCFZ. These samples are designated as BC(sample number)-96 for Bear Camp and LF1-96 for Lower Camp. The location of each sample was marked on the field maps. Samples were taken from within the inner core and outer boundaries of the simple fault zones, at fracture and fault junctions, at or near offset dikes, and areas that showed alteration of the surrounding granodiorite along fracture and fault traces.
**Laboratory Methods**

Once field work was completed, office copies of the field maps were constructed. Each of the three fault zones were redrawn so that the entire fault zone fits on a single sheet. In addition, all three zones were drawn at the same scale (1:100). As a result, direct comparison of the three fault zones to one another is possible. As in the field, the positions of the map points were located relative to the control points and the fracture traces were transferred onto the office maps. Unlike the field maps, the elevations calculated for each map point were also placed on the office maps. Dike traces, along with their offsets, attitudes of fracture and fault traces, and the locations of samples were recorded on the office maps.

Although the field data include location and elevation, the data were recorded in polar coordinates. For three-dimensional computer representation, the field data needed to be converted into rectangular coordinates. To do this, the office maps were digitized into computer files using SigmaScan software. This created x and y coordinates for the map points relative to the primary control point of each fault zone. Intermediate points along fracture and fault traces located on the maps were also digitized as were the traces of dikes.

The elevations calculated in the field could not be digitized directly and were entered into the computer files manually. The elevation of intermediate points and dikes not measured in the field, but digitized into the computer, was calculated by interpolating between bracketing map point elevations. These interpolated elevations, comprising ~63% of all the points, were then added to the computer files.

Once completed, the computer files were transferred into a spreadsheet program, where a color-coded system indicates whether each fracture, fault, or dike trace was exposed, covered, or of uncertain existence. Then the computer files were manipulated using modified software developed at Utah State University (Zheng,
1995). This software graphed and manipulated the three-dimensional fault and fracture data on an SGI Graphics workstation, producing a color-coded three-dimensional picture of the fault zone that can be rotated in space to view the fault zone at any angle.

Thin sections were made from the rock samples in order to perform microstructural analyses of the fault-related rocks. For those rock samples that contained long fracture traces, the thin sections were made sequentially along the entire trace to provide a unbroken view of the fracture. The thin sections were viewed using an Olympus BH-2 petrographic microscope.
FIELD OBSERVATIONS

Bear Camp Fault Zone

The Bear Camp Fault Zone (BCFZ) is the largest and most complex of the three fault zones discussed in this study. The trace of the fault zone extends in a N73°E direction and is ~140 m long. At its eastern end, the fault zone is 12 m wide. The width of the fault zone decreases to 1 m at the western end. There is ~33 m of vertical relief along the BCFZ. Plate 1 is a map view of the fault zone showing the overall geometry of the BCFZ.

The eastern end of the BCFZ is located along the edge of a small northwest-trending drainage basin that is ~20 m wide. Northeast of this drainage basin, evidence for the continuation of the BCFZ is absent. Thus this study assumes that the trace of the BCFZ ends within the drainage basin. Southwestward of the drainage basin, the BCFZ transverses over an area with a slight rise in topography (Fig. 9a). The vertical relief then increases as the fault zone continues up the eastern face of a ridge (Fig. 9b). At the crest of the ridge, the topography flattens out with the fault zone occupying two narrow steps of different elevations on the ridge-top (Fig. 9c). Finally, the fault zone continues down the western face of the ridge (Fig. 9d). On the western side of the ridge, the BCFZ terminates beneath a covered area ~8 m wide.

There is no evidence for the continuation of the BCFZ west of this covered area. Instead, the exposed rock is massive and unfractured with scattered boulders resting on the rock surface. No evidence for a fault zone exists where the trace of the BCFZ would project across the Pacific Crest/John Muir trail. Furthermore, there was no evidence for a fault zone on the western side of Bear Creek. As a result, this covered area is interpreted as the western end of the BCFZ. Because of
Figure 9. Bear Camp Fault Zone. (a) View westward from the eastern edge of the fault zone. Fault zone initially has a gentle vertical relief that increases southwestward towards the ridge in the background. (b) View westward from point E7. The vertical relief along the fault zone increases sharply as the eastern crest of the ridge is approached. (c) View eastward from point F9 of the relatively flat steps along the ridge-top. (d) View eastward up the ridge along the western simple fault zone. The vertical relief on the western side of the ridge is substantially greater than the eastern side. The rocks within the simple fault zone are highly fractured relative to the surrounding host granodiorite.
the reduction in the width of the fault zone at this point, the western end of the BCFZ is thought to be a tip region of a fault zone.

The control point A0 is located within the drainage basin, 11 m from the eastern edge of the fault zone. The highest point on the fault zone (point E42) is 32.76 m above point A0. The elevation of the western end of the fault zone is ~17.8 m higher than point A0.

The trace of the BCFZ changes southwestward from a series of individual fracture and fault traces into a complex array of interacting fractures and faults (Plate 2). At the eastern end, the fault zone consists of parallel to subparallel and non-coplanar fracture traces. Some of these traces coalesce to form a simple fault zone as the fault zone continues southwestward up the east face of the ridge. The other traces form an array of interconnecting fractures and faults that continue up the ridge southeast of the simple fault zone. At the ridge crest, the simple fault zone terminates and its boundary faults continue beyond the simple fault zone as individual fault traces that interact with other fractures and faults. Eventually, this array of fractures evolves to form a second simple fault zone located on the western side of the ridge (Plate 2). Those fracture and fault traces that continue up the eastern side of the ridge which are not part of the simple fault zone either join with those traces between the simple fault zones or branch off into a separate array of fracture and fault traces. On the western side of the ridge, the fault zone consists of a simple fault zone and one individual fracture trace. The simple fault zone disappears beneath the covered area that locates the western end of the BCFZ.

In map view, individual fracture and fault traces form networks in which the traces are parallel or subparallel to each other, and interact among themselves along steps or transfer fractures (Plate 2). These networks, referred to in this study as fracture networks, are connected to one another by obliquely-striking transfer
fractures. The BCFZ contains four fracture networks (Plate 2).

Although cooling joints typically form within a pluton as the pluton cools, outcrop-scale evidence verifying the existence of preexisting joints in the BCFZ is absent. Research by Martel et al. (1988) documented that joints exist within unfaulted outcrops near the BCFZ. Subsequent displacement along the BCFZ may have destroyed any field evidence for jointing within the fault zone. The apparent lack of joints impacts the comparison of these field observations with theoretical fault-growth models. Such implications are presented in the Discussion section.

Fourteen aplite dikes are located within the BCFZ (Plate 1). Only seven of these dike traces cross the entire width of the fault zone. All the dike traces within the fault zone are offset left-laterally by the fault traces. No offset inclusions are present within this fault zone.

The following discussion of the BCFZ begins with a description of the two simple fault zones. A description of the four fracture networks comprising the remaining part of the BCFZ follows. Afterwards, a detailed description of the physical and mineralogical characteristics of the individual fracture and fault traces is given. Then, the characteristics of fracture and fault terminations, junctions, and interactions between fracture and fault traces is presented. Following this will be the results of thin-section analysis on the rock samples removed from the fault zone. Finally, a description of the dike traces, as well as a discussion of the slip distribution along the trace of the BCFZ, is given.

**Simple Fault Zones.** The BCFZ contains two simple fault zones, referred to in this study as the eastern and western simple fault zones, that have the physical characteristics common to simple fault zones as described in the Terminology section. Both simple fault zones are located on opposite sides of the ridge (Plate 2). Neither simple fault zone extends across the flat ridge-top nor do they directly
connect with one another.

The eastern simple fault zone is 25 m long and varies in width from 1.5 to 2.5 m along its trace. The vertical relief increases southwestward along the simple fault zone by 10.5 m. The boundary faults are linear without breaks or steps along their traces. These boundary faults clearly define a separation between the unfractured granodiorite outside the simple fault zone and the fractured rock within the simple fault zone. The boundary faults show evidence for extensive mineralization and some of the exposed fault surfaces contain slickenlines, indicating strike-slip movement along the fault surface.

The northern boundary fault maintains a relatively straight trace between points D19 and D25 (Plate 1). The strike of this boundary fault ranges between 59° and 62°, with the dip varying from 78°SE to 89°SE. In contrast, the southern boundary fault, which extends from point D18 to point D29, is kinked at one location and has a wider range of attitudes. Between points D29 and D26, the attitude of the fault trace varies slightly from 61°, 84°SE to 59°, 80°SE. East of point D26, the attitude of the fault changes to 245°, 84°NW. At point D18, the southern boundary fault bends 18° counterclockwise and continues northeastward away from the simple fault zone as an individual fault trace (Plate 1).

Slickenlines are exposed at only one location along the northern boundary fault surface, 3.2 m southwest of point D22 (Plate 1). These slickenlines have a rake of 4°E. Similarly, slickenlines at point D26 on the southern boundary fault have a rake 4°E. This location is directly across the simple fault zone from where the slickenlines are exposed on the northern boundary fault. Slickenlines exposed at point D18 have a rake of 0°. In this case, no corresponding slickenlines are exposed along the northern boundary fault directly across from this location.

The width of the boundary faults is difficult to determine exactly because the
edge of the fault surface facing into the simple fault zone has been eroded away. As a result, only a minimum value for the width is obtainable. For the eastern simple fault zone, the width of the boundary faults ranges from 5 to 15 mm. In some cases, especially at the northeastern end of the simple fault zone, the entire fault surface has been eroded away, leaving only the exposed surface of the unfractured host granodiorite.

The boundary faults are easily recognized due to the mineralization that has occurred within the fault traces. At the outcrop-scale, this mineralization gives the fault trace a medium to dark green color associated with chlorite-epidote mineralization. Outcrop-scale evidence for quartz mineralization is limited to one elliptical-shaped pocket of quartz located at point D19 (Fig. 10) and visible quartz grains on the slickenlines exposed along the fault surfaces. The scarcity of quartz mineralization within the boundary faults, as well as within the BCFZ as a whole, is

![Quartz and chlorite-epidote mineralization](image)

**Figure 10.** Quartz and chlorite-epidote mineralization within the northern boundary fault of the eastern simple fault zone at point D19. Top of photo is west.
anomalous for this same area (e.g., Segall and Pollard, 1983b; Segall and Simpson, 1986; Martel et al., 1988; Martel, 1990; Christiansen and Pollard, 1997). A possible explanation for this lack of quartz mineralization is given later in this description section. Both boundary faults are surrounded by a zone of altered, unfractured granodiorite, 1 to 3 cm wide on the side of the fault trace outside the simple fault zone. Thin-section analysis reveals that this alteration is the result of altered plagioclase feldspar grains, which give the granodiorite an orange-pink appearance. The alteration zone is not continuous along the trace of each boundary fault, but is randomly distributed along both boundary faults.

The eastern simple fault zone terminates on its western end at the crest of the ridge at points D25 (for the northern boundary fault) and D29 (for the southern boundary fault) (Plate 1). The boundary faults continue southwestward beyond the simple fault zone as individual faults in a fracture network (Plate 2). At the eastern termination of the simple fault zone, both boundary faults disappear beneath a covered area, only to reappear as individual fault traces in another fracture network (Plate 2).

The boundary faults of the eastern simple fault zone define a volume of highly eroded, fractured granodiorite (Fig. 11). The rock between the boundary faults is surprisingly coherent, having a rounded and smooth exposed surface. Brecciation of the host granodiorite, as well as mineral alteration indicating hydrologic flow, is absent. Glacial straitions are present on the surface of some of the rock within the simple fault zone, indicating that some erosion has taken place over time. The erosional appearance of the granodiorite between the boundary faults suggests the possibility that evidence for brecciation was present at one time and has since been eroded away.

Three left-stepping transfer fractures connect the northern and southern
Figure 11. Characteristics of the simple fault zones within the BCFZ. (a) View westward along the eastern simple fault zone. The simple fault zone contains transfer fractures and minor amounts of brecciated and mineralized rock. (b) View eastward along the eastern simple fault zone. The rock within the simple fault zone is relatively coherent, with few transfer fractures and little brecciation. (c) Highly brecciated and mineralized rock within the western portion of the western simple fault zone. Top of photo is north. (d) View eastward along the eastern portion of the western simple fault zone. Notice that the condition of the rock within this portion of the western simple fault zone resembles that shown in (a).
boundary faults to each other. The trace of these transfer fractures strike obliquely from the boundary faults with attitudes of 202°, 74°NW, 205°, 81°NW, and 215°, 78°NW (Plate 1). All these left-stepping transfer fractures dip in the opposite direction relative to the boundary faults on either side (Fig. 12). No outcrop-scale evidence for slip occurring along any of the transfer fractures exists. The transfer fractures have the same chlorite-epidote mineralization found within the boundary faults, however, the presence of quartz could not be verified in the field. The altered granodiorite surrounding the boundary faults also surrounds the traces of these transfer fractures. None of the transfer fractures crossed the boundary faults.

Several fractures branch off from the southern boundary fault towards the fracture network south of the simple fault zone (Plate 2). In contrast, no fractures branch from the northern boundary fault into the host granodiorite north of the simple fault zone.

No dike traces cross the eastern simple fault zone, thereby eliminating the possibility of determining the exact amount of slip along the boundary faults of this simple fault zone. However, dikes are offset by the extensions of both the northern and southern boundary faults. The trace of dike 3 is offset 60 cm along the trace of fault 2 (the northeastern extension of the southern boundary fault) whereas the trace of dike 6 is offset 44 cm along the trace of fault 22 (the southwestern extension of the northern boundary fault) (Plate 1).

Whereas both ends of the eastern simple fault zone are exposed within the BCFZ, the western end of the western simple fault zone disappears beneath a covered area and does not reappear (Plate 2). The western simple fault zone is ~31 m long and decreases in width southwestward from 1.8 to 1 m. The eastern end of this simple fault zone is 13.2 m higher than the western end. The northern boundary fault extends 23 m from point G18 to point G2, whereas the southern boundary fault
Figure 12. Equal-area stereograms of the fractures, faults, dikes, and slickenlines within the BCFZ. All stereograms are lower-hemisphere projections. (a) Poles of fracture and fault traces except for steps and those traces that comprise the fault step complex. The general orientation is northeast-to-southwest, with dips steeply to the southeast. (b) Poles of left-stepping fracture and fault traces. All of these traces dip in the opposite direction to that of fractures and faults in (a). (c) Poles of right-stepping fracture and fault traces. These traces have a dip direction similar to the traces in (a), but opposite to those in (b). (d) Poles of fault traces within the left-stepping fault step complex. The orientation of these traces is similar to the left-stepping traces in (b). (e) Poles of dike traces. The orientation of the dikes within the BCFZ is variable. (f) Rakes of slickenlines. The rakes plot in the same quadrant as Segall and Pollard (1983b), indicating that the last motion on the faults was strike-slip.
North
\[ n = 72 \]
Mean vector = 329°, 10°
Great circle = 59°, 80° S

North
\[ n = 11 \]
Mean vector = 130°, 10°
Great circle = 220°, 80° W

North
\[ n = 7 \]
Mean vector = 345°, 14°
Great circle = 75°, 76° S

North
\[ n = 5 \]
Mean vector = 117°, 14°
Great circle = 207°, 76° W

North
\[ n = 13 \]

North
\[ n = 9 \]
extends the full 31 m from point F21 to point G3 (Plate 1). This disparity in boundary fault lengths is due to the northern boundary fault disappearing beneath a covered area east of point G18. In contrast, the southern boundary fault is exposed along the entire trace of the simple fault zone. As with the eastern simple fault zone, the boundary faults of the western simple fault zone are linear and subparallel to each other. However, the western simple fault zone contains a right step along the northern boundary fault.

The attitudes of both boundary faults are fairly consistent and no major changes in dip direction occur along either boundary faults. The attitude of the northern boundary fault trace ranges between 55°, 76°SE and 62°, 85°SE. A right step is present along the northern boundary fault at point G5 (Plate 1). At this point, the boundary fault steps to point G6 and continues southwestward to point G2. Points G5 and G6 are connected by a portion of dike 13 (Fig. 13). The fault trace between points G2 and G6 continues northeastward from point G6 to point G7, where the fault terminates as a horsetail splay. The southern boundary fault

Figure 13. Trace of dike 13 acting as a step along the northern boundary fault of the western simple fault zone. Top of photo is north.
maintains a fairly consistent attitude, ranging between 60°, 80°SE and 61°, 81°SE.

Slickenlines exposed on the northern boundary fault at point G6 have a rake of 5°E. In contrast, the slickenlines exposed on the southern boundary fault at point G3 have a rake of 11°E. The six degree difference between the two rakes may be due to the fact that point G6 is not located directly across the simple fault zone from point G3 (Plate 1), or that point G6 is located on the right step along the northern boundary fault (Fig. 13).

As with the eastern simple fault zone, only a minimum value for the width of the boundary faults is obtainable. For the western simple fault zone, the boundary faults range in width from 5 to 10 mm.

The outcrop-scale mineralogy of the boundary faults is similar to the eastern simple fault zone. Chlorite-epidote mineralization is pervasive along both fault surfaces. Quartz pockets are absent along the fault traces, but quartz mineralization is visible along the slickenlines exposed at points G3 and G6. In addition, alteration zones of the surrounding granodiorite are present at random locations along the outside edges of both boundary faults.

The eastern end of the western simple fault zone is more complex than the western end of the eastern simple fault zone. Whereas the two boundary faults of the eastern simple fault zone continue southwestward beyond the simple fault zone as individual fault traces, the boundary faults of the western simple fault zone branch into several fault traces that extend northeastward beyond the simple fault zone into the adjoining fracture network (Plate 2). A transfer fault (fault 32) branches off from the southern boundary fault at point F21 and extends into the topographically higher fracture network that crosses the ridge-top (Plate 1). The trace of the southern boundary fault continues northeastward beyond the simple fault zone from point F21
as fault 25. The northern boundary fault branches off a transfer fault trace at point G14 (Plate 1). From here, this transfer fault links the northern boundary fault to the trace of fault 27 at point G15. A comprehensive description of the interaction between the two simple fault zones and the fracture network between them is given below in the fracture network portion of this section. At the western end of the western simple fault zone, the boundary faults disappear beneath the covered area which defines the end of the BCFZ. No fracture or fault traces branch off from the boundary faults of the western simple fault zone into the surrounding host granodiorite.

Unlike the eastern simple fault zone, the rock bounded by the western simple fault zone is highly brecciated with widespread mineral alteration existing within the brecciated host granodiorite (Fig. 11c). The amount of brecciation and mineral alteration is widespread at the western end of the simple fault zone, but decreases northeastward and upwards (Fig. 11d). At the eastern end of the simple fault zone, the rock within the simple fault zone begins to resemble the rock at the western end of the eastern simple fault zone. Unlike the eastern simple fault zone, no glacial striations are present on the exposed rock surfaces within the western simple fault zone.

Only one mappable transfer fracture exists within the western simple fault zone. This transfer fracture branches from the southern boundary fault at point G13 and connects with the northern boundary fault trace at point G18 (Plate 1). This transfer fracture does not appear to offset the trace of dike 11 between points G19 and G18. The dike trace is beneath a covered area south of the transfer fracture, however, making any offset of the dike trace by this transfer fracture difficult to determine.

The traces of dikes 11 and 13 cross the entire western simple fault zone and
the trace of dike 10 crosses the southern boundary fault (Plate 1). The traces of these dikes within the simple fault zone are not continuous and difficult to locate, making offset measurements potentially inaccurate. The complications associated with following these dike traces across the western simple fault zone, as well as estimating the offset measurements, are discussed below in the section describing the dikes and slip distribution within the BCFZ.

Whereas both simple fault zones within the BCFZ have features typical of simple fault zones, such as parallel to subparallel boundary faults that define a volume of fractured rock, the two simple fault zones are not similar in appearance. Although the physical appearance of the granodiorite within both simple fault zones is similar near the top of the ridge, both simple fault zones have completely different physical appearances at the opposite ends. The rock within the western simple fault zone is highly brecciated at the western end (Fig. 11c). Rock fragments have sharp, angular edges and contain pervasive fractures associated with brecciation. Furthermore, alteration of the brecciated rock to a chlorite-epidote assemblage is widespread throughout the rock within this simple fault zone. As one goes northeastward up the western simple fault zone, the amount of brecciation and alteration decreases (Fig. 11d). This difference in appearance between the two simple fault zones may be the result of different amounts of slip occurring along the simple fault zones.

Fracture Networks. The geometry of exposed fracture and fault traces allows for the individual traces to be grouped into arrays of parallel to subparallel fractures and faults called fracture networks. Within each fracture network, the individual fracture and fault traces interact among themselves by way of steps and transfer fractures (Plate 2). These fracture networks do not contain simple fault zones, but the boundary faults of both simple fault zones extend into adjacent
fracture networks. The fracture networks connect with one another by using obliquely-striking transfer fractures or faults. It is these obliquely-striking transfer traces between groups of similarly oriented fractures and faults that permit the division of the BCFZ into specific fracture networks.

The BCFZ is divided into four fracture networks (Plate 2). Fracture network I contains those fractures or faults between the eastern simple fault zone and the eastern end of the BCFZ. Fracture network II contains all the fractures and faults between the eastern edge of the BCFZ and the eastern crest of the ridge, south of the eastern simple fault zone. Fracture network III is made up of all the fracture and fault traces present along the top of the ridge between the two simple fault zones. Fracture network IV contains those fracture and fault traces located on the ridge-top south of fracture network III. This portion of the BCFZ section describes the geometry of each fracture network and how the fracture networks interact with one another.

Fracture network I begins at points D18 and D19, which locates the eastern end of the eastern simple fault zone, and continues northeastward to the edge of the drainage basin which marks the end of the BCFZ (Plate 2). This fracture network consists of fault traces 1 to 9, along with their associated fracture traces (Plate 1). The northern boundary fault trace from point D19 is projected across the covered area to point D15, where it continues into the fracture network as fault 1 (Plate 1). The southern boundary fault continues northeastward as fault 9, which terminates at a junction with fault 1 at point D1. From point D1, only the trace of fault 1 continues northeastward. From Plate 1, it appears that the northeastern end of the fault 9 trace begins by branching from the fault trace which later becomes the northern boundary fault. The only attitude taken along the trace of fault 9 has a measurement of 236°, 87°NW.
The trace of fault 1 continues eastward to point C7 (Plate 1). An attitude of 60°, 76°SE was measured along this fault trace at point C8. At point C7, a left step connects this fault to a parallel fracture trace at point C5. From point C5, this fracture continues northeastward until it too steps left, just east of the covered area, to point C4. From point C4, a second non-coplanar fracture trace continues northeastward until disappearing beneath a the covered area (Plate 1). This second fracture trace has an attitude of 60°, 78°SE at point C3. This fault-fracture interaction illustrates how left steps form the long, continuous fracture and fault traces seen in fracture network I.

At point D2, fault 2 branches from the trace of fault 1 and continues northeastward to point D10 (Plate 1). At this point, the trace of fault 2 disappears beneath a covered area with an attitude of 63°, 82°SE.

North and subparallel to the traces of faults 1 and 2 are a series of parallel fault traces. Beginning at the northeastern end of the BCFZ, the traces of faults 3 and 4 emerge from the drainage area and extend southwestward while maintaining a constant 60 cm distance between themselves (Plate 1). Both fault traces offset the traces of dikes 1 and 2, but the offsets are different for each fault trace. Fault 3 has offset the dikes between 60 cm and 64 cm, whereas fault 4 has offset the same dikes by only 28 cm and 32 cm. Both fault traces continue beneath a covered area and reappear to the southwest with the same 60 cm spacing between their traces. Eventually the trace of fault 3 steps to the left and connects with fault 4 at point C1 (Plate 1). The trace of fault 4 continues southwestward for ~2 m until it terminates at a junction with fault 6.

At point A12, the trace of fault 5 appears from a covered area and curves until it enters an area of localized branching and crossovers (Plate 1). At point A12, this fault trace has an attitude of 70°, 79°SE and slickenlines that have a rake of 7°E.
Approximately 2 m southwest of point A13, the trace of fault 5 terminates and a transfer fault strikes to the southwest. This transfer fault, fault 6, has attitudes ranging between 234°, 84°NW and 233°, 88°NW, consistent with the orientations of other left-stepping faults and fractures in the BCFZ (Fig. 12b).

From the area of localized branching and crossovers, three individual traces emerge (Plate 1). The northernmost trace is fault 7. This fault trace extends southwestward, parallel to the overall trend of the fractures and faults comprising the fracture network, with an attitude of 59°, 73°SE. At point A15, the trace of fault 7 terminates by dying out at a tip. The middle trace is a fracture which extends from 10 m northeast of point B7 to point B13 (Plate 1). An attitude measuring 61°, 88°SE was measured along this fracture trace at point B7. While this fracture is parallel to the overall trend of the fracture network, a jog along the fracture trace exists between points B9 and B12 (Plate 1). This jog is the result of the host rock being broken away from the outcrop and moved to the northwest. Matching the rock back to its original position gives the fracture a relatively straight trace. At point B13, the fracture trace steps to the left to connect with fault 8. The third trace originating from the crossover area is fault 8 and it extends from ~4 m northeast of point A14X to point B17 (Plate 1). This fault maintains a straight trace with attitudes ranging between 59°, 84°SE and 60°, 81°SE. The trace of fault 8 terminates at the northeastern end by dying out at a tip. In contrast, a horsetail splay is present at the southwestern endpoint of fault 8.

At points D19 and D15 along the trace of fault 1, several fractures branch off in an oblique direction from the fault trace (Plate 1). These branch fractures do not offset the intersecting trace of dike 3. The fracture trace branching from point D19 continues to the northeast, only to have several fractures branch off to the left, producing a splay-like structure. The fracture trace branching from point D15
appears to connect with the fracture trace originating from point D19 beneath the covered area west of point D13. Once exposed, this combined fracture trace continues northeastward to point D12. A step connects point D12 to the horsetail splay at point B17 (Plate 1). Whereas this step physically connects with the trace of fault 8, no outcrop-scale evidence along the step exists to indicate that slip was transferred to or from the trace of fault 8. Possibly, the step developed originally as one of the splay fractures comprising the horsetail splay.

Fracture network I interacts with the eastern simple fault zone and fracture network II (Plate 2). The connection with fracture network II is made by a fracture trace branching from point D6 on fault 2 and continuing in an oblique direction to point C17 in fracture network II (Plate 1).

Like fracture network I, fracture network II begins at the edge of the drainage basin marking the eastern end of the BCFZ (Plate 2). Southwestward, fracture network II terminates as a series of tips or connections with fracture networks III and IV. Fracture network II consists of fault traces 10 to 20, along with their associated fractures and steps (Plate 1). Whereas the fracture and fault traces comprising fracture network II have the parallelism and linearity seen within the other fracture networks, the large number of right-stepping transfer fractures and faults is unique to fracture network II.

The eastern end of this fracture network is represented by the trace of fault 11. Fault 11 begins 1 m northeast of point A1 and extends westward to point A11 (Plate 1). At the northeastern end of fault 11, the traces of dikes 1 and 2 are offset by an estimated amount of 190 cm and 170 cm. Another small dike (unnumbered in this study) intersects the trace of fault 11 at point A2, but no continuation of this dike trace north of fault 11 is present (Plate 1). Emerging from a covered area at point A5 with an attitude of 69°, 85°SE, the trace of fault 11 continues southwestward until
terminating at point A11 by dying out at a tip. Right-stepping transfer fractures branch off from the trace of fault 11 and connect with the parallel, but non-coplanar fault 12 (Plate 1). All of these right-stepping transfer fractures have attitudes with dip directions to the southeast (Fig. 12c).

The trace of fault 12 begins at point A17 and extends westward to point A22 (Plate 1). This fault offsets the trace of dike 3 by 50 cm at point A20. An attitude of 55°, 78°SE was taken along fault 12 at point B6. The trace of fault 12 terminates on both ends by dying out at a tip. At point A18 on fault 12, a right-stepping transfer fault, fault 13, branches off and connects with the trace of fault 16 at point A26 (Plate 1). The trace of fault 13 has an attitude of 86°, 71°S. At a junction 2 m northeast of point A21 on fault 12, a right-stepping transfer fracture branches off and connects the trace of fault 12 to a parallel, non-coplanar fracture trace. This fracture trace, in turn, is connected to the parallel, but non-coplanar trace of fault 14 by another right-stepping fracture (Plate 1). The trace of the transfer fracture branching from fault 12 has an attitude of 52°, 78°SE.

The trace of fault 14 extends from a covered area to a stepover north of point E10 (Plate 1). This fault trace has an attitude of 57°, 80°SE and exposed slickenlines have a rake of 34°E. This is the largest rake within the BCFZ. A stereogram of all the rakes in the BCFZ (Fig. 12f) resembles the results obtained in the Bear Creek region by Segall and Pollard (1983b, Fig. 4). Therefore, the slickenlines within the BCFZ indicate that the last motion on the faults was strike-slip (Segall and Pollard, 1983b). The stepover at the western end of fault 14 steps towards the left with one of the transfer faults comprising the stepover having an attitude of 218°, 76°NW (Plate 1).

The trace of fault 15 extends westward from the stepover with fault 14 to point E12 (Plate 1). Attitudes of this fault trace range between 57°, 75°SE and 57°,
77°SE. In addition, fault 15 offsets the traces of dikes 4 and 5 by 29 cm and 23.5 cm, respectively. The trace of fault 15 terminates at point E12 by dying out at a tip.

At point A24, the trace of fault 16 emerges from beneath a covered area. There was no evidence for this fault trace east of the covered area. Southwestward, fault 16 extends to a point 90 cm southwest of point B5, where a stepover connects fault 16 to a fracture trace that continues southwestward to point B4 and disappears beneath a covered area (Plate 1). An attitude of 65° 85°SE was taken along fault 16 at point B1. An attitude of 68°, 67°SE was obtained from the fracture trace which forms the stepover west of point B5. A fracture trace branching to the northeast from the trace of fault 16 at point A23 extends to point A25, where it disappears beneath a covered area (Plate 1). Southwest of point B1, the trace of fault 17 branches off to the right from fault 16 and extends to point B2. At point B2, a stepover exists between points B2 and B3 (Plate 1). Point B3 marks the end of fault 17 and the beginning of fault 18.

From point B3, the trace of fault 18 extends southwestward up the eastern slope of the ridge to a point 5 m southwest of point E16 (Plate 1). The trace of fault 18 is relatively straight with minor bending at a few locations. The attitudes of fault 18 ranges between 56°, 80°SE and 63°, 89°SE. Slickenlines exposed on the fault surface have a variety of rake, from 11.5°E at point E7 to 6°E southwest of point E6. The trace of dike 3 intersects fault 18 at point C17, but the continuation of this dike south of the fault trace is covered (Plate 1). Projecting the dike trace across the covered area gives an estimated 160 cm of offset along the trace of fault 18. The trace of fault 19 branches off to the left from fault 18 at a junction 3.5 m southwest of point E6 (Plate 1). This transfer fault (fault 19) connects fault 18 with the trace of fault 14. Locating the southwestern end of fault 18 is somewhat problematic. An exposed vertical surface of the fault exists, but no fault trace was present on the
horizontal outcrop surface. Thus continuation of this fault trace southwestward is shown as uncertain on Plate 1.

Between the trace of fault 18 and the eastern simple fault zone there are several fracture and fault traces which interact among themselves, the surrounding traces within the fracture network, fracture networks III and IV, and the eastern simple fault zone (Plate 2). From point D5 on the transfer fracture that connects the trace of fault 2 of fracture network I to point C17 on fault 18, the trace of fault 10 begins and extends southwestward to point E4 on fault 18 (Plate 1). The trace of fault 10 appears to offset the trace of dike 3 at point C19 by 52 cm. An attitude of 46°, 80°SE was taken from fault 10 at the edge of a covered area 1 m northeast of point E1.

From point E8, a fracture trace extends southwestward to point E22 with an attitude of 74°, 73°SE (Plate 1). The northeastward projection of this trace from point E8 towards point D18 appears reasonable in map view, but no exposed fracture trace on the outcrop was found. At point E22, this fracture trace branches into two, possibly three, fractures; one extends to point E4 on the trace of fault 18 and the other, with attitudes ranging between 68°, 76°SE and 69°, 60°SE, to a point 1.5 m southwest of point E21 (Plate 1). At the endpoint southwest of point E21, the second fracture trace intersects with another fracture which branches from a point on the southern boundary fault (Plate 1). The fracture trace originating from the southern boundary fault has an attitude of 215°, 74°NW, indicating that it is a left-stepping transfer fracture. From field observations, it appears that a third fracture trace may originate from point E22 and extend to point E19 (mapped on Plate 1 as an uncertain fracture). However, no fracture trace is present on the outcrop between these two points. Possibly, the fracture surface did not extend up to the outcrop surface, as there is a 2.53 m difference in height between points E19 and E22.
From a junction at point D26 on the southern boundary fault of the eastern simple fault zone, a fracture trace extends in a southwestern direction through point E20 and terminates at point E19 (Plate 1). The attitudes of this fracture trace (29°, 85°SE and 11°, 87°SE) have dip directions suggesting that this fracture trace is not a left-stepping transfer fracture because all left-stepping transfer fractures and faults dip to the northwest (Fig. 12b).

At point E19, the trace of fault 20 extends southwestward up the slope of the ridge to point E18 (Plate 1). A transfer fracture branches off to the left from the trace of fault 20 at a junction 3.8 m southwest of point E19 and connects with the trace of fault 18 at point E15. The attitude of this transfer fracture is 200°, 82°NW. At point E18, the trace of fault 20 separates into three individual traces (Plate 1). One trace branches to the left to connect with fault 18 at point E16. A second trace, fault 28, continues southwestward with the same attitude of fault 20 (63°, 82°SE) into fracture network IV. The third trace, fault 21, extends into fracture network III. Slickenlines exposed along the fault surface at point E18 have a rake of 22°E.

Anomalous to the fault and fracture traces comprising fracture network II is the fracture trace between points C9 and C16, located in the northeast portion of the fracture network (Plate 1). The trace of this fracture does not interact with any of the fault or fracture traces located within fracture network II. Instead, both ends disappear beneath covered areas and do not reappear on the other side of these covered areas. Although this trace is parallel to and in between the traces of faults 2 and 11, the attitude of this fracture trace is 252°, 86°NW, a dip direction characteristic of left-stepping transfer traces (Fig. 12b). All the fractures branching from this trace step to the left, but do not connect with any of the other fractures or faults within fracture network II.

Fracture network III contains those fractures and faults that connect the two
simple zone to each other, forming a left step between the simple fault zones (Plate 2). Fracture network III consists of fault traces 21 to 26, as well as their associated fracture traces and a fault step complex (Plate 1). As previously mentioned, all four boundary faults of the two simple fault zones extend beyond the simple fault zones into this fracture network as individual fault traces (Plate 2). Yet the northern boundary fault of the eastern simple fault zone does not directly connect with the northern boundary fault of the western simple fault zone, nor does the southern boundary fault of the eastern simple fault zone directly connect with the southern boundary fault of the western simple fault zone (Plate 2). The northern boundary fault of the eastern simple fault zone continues across the ridge-top from point D25 as fault 22 (Plate 1). This fault trace has attitudes ranging between 56°, 81°SE and 57°, 83°SE and offsets the trace of dike 6 by 44 cm. The trace of fault 22 terminates with fault 24 at a junction northeast of point E28.

The southern boundary fault of the eastern simple fault zone continues southwestward to point E33 as fault 23 (Plate 1). Southwest of point E33, this fault trace disappears beneath a covered area. Within this covered area, the trace of fault 23 either continues to point E32 or to point F6. The exposed trace extending northeastward into the eastern simple fault zone from point E32 appears to be a fracture, whereas the trace extending southwestward from point E32 appears to be a fault. The exposed trace between points F6 and F7 lacks outcrop-scale evidence for faulting and is considered here to be a fracture. As a result, it would appear that the trace of fault 23 continues to point E32. From point E32, fault 23 continues to point E31, where it separates into three individual traces (Plate 1). One trace, fault 24, continues to point E28 with an attitude of 70°, 86°SE and extends southwestward into a fault step complex. The second trace continues from point E31 to point F9 and eventually terminates at a junction with the trace of fault 25 beneath a covered area.
The attitude of this fracture trace between points F9 and fault 25 is 226°, 86°NW, similar to left-stepping transfer fractures. Finally, the third trace extends southwestward as the continuation of fault 23 to point F8 and a junction with the trace of fault 27.

From the western simple fault zone, the southern boundary fault continues northeastward beyond the simple fault zone to point F4 as fault 25 (Plate 1). At point F4, this fault trace steps to the left, connecting with the trace of fault 21, which originated from the southwestern end of fracture network II. Attitudes of fault 25 range between 68°, 75°SE and 70°, 79°SE. Slickenlines exposed along the fault surface at point F3 have a rake of 8°W. Similarly, slickenlines exposed along the trace of fault 24 at point E29, 3 m northwest of point F3, have a rake of 18°W. These two locations are the only ones within the BCFZ where the exposed slickenlines have rakes to the west. Fault 25 also had the greatest amount of offset of any fault trace within the BCFZ. Between points F1 and F2, this fault offsets the trace of dike 8 by 2.07 m (Plate 1).

The trace of the northern boundary fault continues northeastward beyond the western simple fault zone into the fracture network as fault 26 until point F15 (Plate 1). The attitude of this fault trace is 59°, 73°SE and the trace offsets the trace of dike 9 by 70 cm. Northeast of point F15, fault 26 becomes part of a left-stepping fault step complex which is described below.

The trace of fault 21, which begins in fracture network II and extends to point F6, continues through fracture network III as fault 27 (Plate 1). This fault trace extends southwestward across the ridge-top to point G15, where the slip appears to be transferred between this fault trace and the northern boundary fault of the western simple fault zone by a transfer fault branching off to the left from point G15. From point G15, a fracture trace continues southwestward, parallel to the western simple
fault zone, with attitudes ranging between 57°, 81°SE and 63°, 80°SE. At point G23, this fracture trace dies out at a tip (Plate 1). Along the trace of fault 27, the traces of dikes 8 and 9 are offset 1.83 m and 1.22 m, respectively; the fault step complex between points F11 and F18 is bisected; and several transfer fractures with attitudes of 226°, 86°NW and 229°, 78°NW branch off to the left connecting the trace of fault 27 with the trace of fault 25 (Plate 1).

The fault step complex is an area of left-stepping fault traces that connect the northern boundary fault of the western simple fault zone to the eastern simple fault zone (Plate 2). The fault step complex consists of fault traces 24, 26, and 27, as well as eight transfer faults (Fig. 14). Within the fault step complex, the trace of dike 8 is offset three times by amounts between 19 and 183 cm. The left-stepping transfer faults all dip in a northwest direction, whereas the traces of faults 26 and 27 dip to the southeast (Figs. 12a, 12b). The rock within the complex is more angular and broken up than the surrounding granodiorite, but is not brecciated like the rock

Figure 14. Drawing of the fault step complex within the BCFZ. Slip is concentrated on the through-going trace of fault 27. See Plate 1 for location.
within the western simple fault zone. Alteration of the granodiorite surrounding
the fault traces within the fault step complex is widespread.

Fracture network IV begins at point E18 and extends southwestward across
the ridge-top south of fracture network III (Plate 2). This fracture network consists
of fault traces 27 to 33 (Plate 1). Although adjacent to fracture network III, fracture
network IV is located on a topographically higher portion of the ridge crest than
fracture network III. Fracture network IV is relatively self-contained, only
connecting with fracture network II at point E18 and fracture network III at point
F21.

From point E18, the trace of fault 28, the possible continuation of fault 20,
extends southwestward over the ridge-top to a point 4.6 m southwest of point E38
(Plate 1). At this point, the fault trace terminates as a horsetail splay. The curve of
the horsetail splay fractures indicates left-lateral slip along fault 28. The trace of dike
8 is offset 20 cm at a point northeast of the horsetail splay. This fault trace has an
attitude of 77°, 75°SE at point E38.

At point E34, the trace of fault 29 branches to the right from fault 28 and
continues to point E37 (Plate 1). Approximately 1.4 m northeast of point E37, the
trace of fault 30 begins and extends southwestward, subparallel to fault 28. The trace
of fault 30 terminates by simply dying out at a tip. Fault 30 offsets the trace of dike
8 by 27 cm.

The trace of fault 29 terminates at point E37 by merging with fault 31 (Plate
1). From this point, the trace of fault 31 extends southwestward, subparallel to both
faults 28 and 30. Between points E39 and E43, the attitude of fault 31 ranges
between 85°, 71°SE and 90°, 75°S. At point E43, the attitude of this fault trace
changes to 58°, 88°SE. The attitude of fault 31 changes again 1.5 m northeast of
point E44 to 54°, 74°SE. The trace of fault 31 offsets the traces of dikes 8 and 9 by
48 cm and 66 cm, respectively. Southwest of point E43, a fault trace branches to the right from fault 31 and connects with the traces of fault 25 and the southern boundary fault at point F21 (Plate 1). This transfer fault, fault 32, is the connection between fracture networks III and IV. Two attitudes were obtained from the trace of fault 32: 69°, 77°SE and 101°, 84°SW. The attitudes of fault 32 and other right-stepping fracture or fault traces illustrate an interesting characteristic of the BCFZ. All fracture and fault traces that step to the left have a surface that dips to the northwest, opposite to that of the dominant set of northeast striking and steeply southeast dipping faults (Figs. 12a, 12b). In contrast, right-stepping fracture and fault surfaces do not have such a restriction. Given that the BCFZ is a left-lateral fault zone, this characteristic may suggest a relationship between the overall direction of slip along a fault zone and the dip direction of particular fracture and fault surfaces.

A single fault trace, fault 33, extends parallel to the other faults within fracture network IV, but does not interact among them (Plate 1). The trace of fault 33 begins in the northeast at a tip on the outcrop and continues southwestward until disappearing beneath a covered area. The attitude of this fault trace is 59°, 90°S. At point E41, this fault trace offsets the trace of dike 9 by 20 cm.

**Individual Fractures and Faults.** This portion of the BCFZ section describes the characteristics of the individual fracture and fault traces, such as their overall physical features, mineralization, alteration of the surrounding rock, and subsidiary fracturing. In addition, physical features of some fracture and fault traces which deviate from the general characteristics present within the BCFZ are given.

Generally, all the fracture and fault traces within the BCFZ are linear. The traces exposed on the outcrop have relatively straight trends, bending slightly at some points or at junctions. This linearity suggests that the fractures and faults are planar features in three dimensions. Exceptions to this observation are discussed below.
The linearity of the traces allows projecting the traces across covered areas in order to find their continuations. Thus it is relatively easy to follow the fracture and fault traces within the BCFZ. Fracture and fault traces are tens of meters long. The width of an individual trace is not consistent. Instead, the width of a trace can vary from 1 to 40 mm, with the average width being ~5 to 7 mm. The margins of the traces are consistently sharp, juxtaposing unfractured and unmineralized granodiorite next to the highly altered material within the trace. According to Christiansen (1994), the perpendicular normal strain is discontinuous to the in-plane shear strain at the transition between the host granodiorite and a strike-slip fault trace, thereby producing a sharp, rather than gradational, margin.

The spacing between parallel to subparallel fracture and fault traces ranges from 30 cm to 7 m. Figure 15 is a histogram of 95 spacing measurements taken from the BCFZ. The distance between traces clusters at 150 ± 50 cm, and the number of measured spacings decreases smoothly as the distance between traces increases (Fig. 15). Of the 95 spacing measurements taken, 82 (86%) are less than 3 m.

The degree of mineralization along the horizontal and vertical traces of fracture or faults varies along the length of the trace. This field investigation noted that there was no consistent pattern as to the width, composition, or location of mineralization along a particular trace. Chlorite-epidote mineralization is pervasive within the fractures and faults seen in the BCFZ whereas quartz mineralization is not as widespread. The widespread distribution of chlorite-epidote mineralization suggests that the faults within the BCFZ are interconnected enough to be through-going passageways for hydrologic flow. In outcrop-scale, the presence of quartz mineralization appears to be restricted to just fault traces. Even then, pockets of quartz are located randomly along the fault trace. Where quartz is present, it may be surrounded by a chlorite-epidote rim, bordered by chlorite-epidote mineralization on
Figure 15. Histogram of the distances between parallel to subparallel fracture and fault traces in the BCFZ. Ninety-five spacing measurements were obtained from within the fault zone, of which 82 measurements are less than 3 m. In order to permit the direct comparison of fracture and fault trace spacing in one fault zone with the trace spacing in another fault zone (i.e., the LCFZ in Fig. 36), the histogram was constructed such that the area of each individual bar is equal to the percentage of spacing measurements within each 10-cm interval. To calculate this: \( H = \frac{P}{W} \) where \( H \) is the height of the 10-cm interval, \( P \) equals the percentage of spacing measurements falling within a particular 10 cm interval divided by the total number of measurements obtained, and \( W \) is 10 cm.
only one fault surface, or directly in contact with the host granodiorite.

Quartz pockets within fault traces commonly terminate by blending with the chlorite-epidote mineralization. Some locations, however, have a sharp transition between the two different types of mineralization (Fig. 16). As with quartz, elliptically-shaped pockets of chlorite-epidote are present within a few of the fracture traces (Fig. 17). These pockets tend to be 2 to 4 mm in width and have a maximum length of \( \sim 5 \text{ cm} \). As the fracture trace continues away from a chlorite-epidote pockets, the width of the trace becomes smaller than the pocket and may lack outcrop-scale evidence of mineralization.

A characteristic observed within the mineralized fracture and fault traces is a clear indication that episodic chlorite-epidote mineralization had occurred within the traces. In outcrop, the chlorite-epidote mineralization within an individual trace is different shades of green. Several shades of this mineralization was found to exist at the same location within some traces. Commonly, these different shades of color are found side-by-side, as if one episode of mineralization was followed by a second episode that developed between the first episode and the host granodiorite. The difference in mineralization color also appears to coincide with differences in durability because the same shade of chlorite-epidote mineralization breaks off from a trace as a unit, or erodes such that one shade of mineralized material rests higher along the trace than another. In some cases, the different mineralization episodes crosscut one another, but there is no consistency in this crosscutting as darker mineralization crosscuts lighter mineralization at some locations and lighter mineralization crosscuts the darker mineralization at other locations along the same trace. In outcrop, some fracture and fault traces do not have episodic chlorite-epidote mineralization whereas others indicate that as many as three distinct mineralization episodes had occurred. Evidence for episodic chlorite-epidote mineralization is also
Figure 16. Abrupt transition between quartz and chlorite-epidote mineralization along a fault trace. The width of the quartz mineralization increases as one goes away from the transition point with the chlorite-epidote mineralization. Top of photo is north.

Figure 17. Chlorite-epidote pockets within a fracture trace. The chlorite-epidote pockets are wider than the overall fracture trace. Black eraser locates point A25. Top of photo is north.
present within fractures and faults exposed in the vertical plane. Thin section analysis (see below) confirms the presence of episodic chlorite-epidote mineralization. Whether these mineralization episodes occurred before, during, or after slip along an individual fracture or fault trace is not determinable at the outcrop-scale.

The alteration of the granodiorite surrounding the boundary faults of the two simple fault zones is also widespread along individual fracture and fault traces. As with the boundary faults, these alteration zones may not be ubiquitous along an individual trace. Instead, these alteration zones may be randomly distributed along the length of a fracture or fault trace. The altered granodiorite, having a bleached appearance, extends several centimeters away from the trace into the host rock. Typically, fracture and fault traces surrounded by these alteration zones tend to stand up as raised ribs, which Segall and Pollard (1983b) attribute to the altered granodiorite being more resistant to erosion than the nearby unaltered granodiorite.

Whereas the fracture and fault traces exposed along the outcrop can be described as simple linear features, those areas where traces are exposed in the vertical direction reveal that a complex arrangement of fracturing occurs in the vertical dimension. Fracture and fault traces exposed in the vertical plane consistently are surrounded by an array of subsidiary fractures surrounding the main fracture trace. These subsidiary fractures may be parallel to subparallel, or oriented obliquely, to the main trace (Fig. 18), and tend to interact with both the main trace and each other. The subsidiary fractures have smaller widths than the main trace, usually between 1 and 4 mm. As with the main trace, mineralization to a chlorite-epidote assemblage is present within the subsidiary fractures. Outcrop-scale evidence for quartz within the mineralized subsidiary fractures exposed in the vertical plane is absent. In addition, outcrop-scale evidence for slip along any of the
Figure 18. Photographs of the secondary fractures associated with fracture and fault traces exposed in the vertical plane. (a) View westward from the covered area along the trace of fault 18, east of point E7. (b) View westward from the covered area along the fracture trace connecting points D13 and D20.
secondary fractures exposed in the vertical plane is absent. The degree of chlorite-
epidote mineralization and the lack of slip indicators suggests that the subsidiary
fractures act primarily as fluid channels rather than slip planes.

Several exceptions to the general characteristics of fracture and fault traces
presented in this section exist. The trace of fault 19 is a left-stepping transfer fault
which connects fault 18 to fault 14 (Plate 1). In map view, this fault trace appears as
two distinct linear traces. Actually, the fault is a composite of two nonlinear and
nonparallel traces. One of these traces is gently curving and cuts across the second
trace, which is made up of a series of fractures connected to one another at right
angles (Fig. 19). Both the curved and stair-step traces are mineralized to a chlorite-
epidote assemblage, but the curved trace is wider and appears to have undergone a
greater amount of mineralization. No alteration zone within the granodiorite
surrounding these traces is present. The question as to which trace developed first is

![Curving fault trace](image1)

Stair-stepping fault trace

**Figure 19.** The trace of fault 19 having two distinct fault geometries. The
curving trace is wider than the stair-stepping trace. Both traces contain
chlorite-epidote mineralization. Top of photo is north.
not determinable by field relationships. However, the thickness of the mineralized material within the curved trace suggests that it has acted as a better conduit for fluid flow than the stair-stepping trace.

The transfer faults comprising the fault step complex in fracture network III (Fig. 14) are another exception to the general characteristics within the BCFZ. Although these transfer faults are mineralized to a chlorite-epidote assemblage and are surrounded by altered granodiorite, the width of the altered granodiorite is greater than the alteration that surrounds the fracture and fault traces outside of the fault step complex. Furthermore, many of the transfer fault traces comprising the fault step complex lack the linearity typical present within the BCFZ. Instead, traces in the fault step complex tend to be gently curved.

Finally, one fracture trace displays a structure unique within the BCFZ. The left-stepping transfer fracture branching from the trace of fault 18 at point E15 towards fault 20 contains a series of en echelon fractures that cross the main fracture trace, forming a zipper-like structure (Fig. 20). These en echelon fractures, as well as the main fracture trace, have been mineralized to a chlorite-epidote assemblage. In addition, an alteration zone within the host granodiorite encompasses not only the main fracture trace, but the en echelon fractures as well. The length of the individual en echelon fractures decreases as the trace of the main fracture continues towards faults 18 and 19. Similarly, the width of the main fracture trace, as well as the width of the altered granodiorite, decreases towards the junctions with the two fault traces. Eventually, the main fracture trace continues towards the traces of faults 18 and 20 without any en echelon fractures or an alteration zone.

Terminations, Junctions, Crossovers, Steps, and Stepovers. This portion of the BCFZ section describes how fracture and fault traces terminate, as well as the mineralization formed at their endpoints. In addition, the characteristics of junctions
and crossovers between individual traces, as well as steps and stepovers which connect non-coplanar traces to one another, are described.

Fracture traces terminate by a limited number of styles (Table 1). Of the 43 fracture traces mapped in the BCFZ, 60 endpoints are a junction with another fracture or fault trace, 19 endpoints are covered, and seven endpoints simply die out at a tip on the outcrop (Fig. 5a). Chlorite-epidote mineralization within the fracture trace may extend to the tip of the fracture trace or may terminate short of the endpoint. Stepovers and splay fractures were not present at the ends of any of the fracture traces within the BCFZ.

Figure 20. Photograph and line drawing of the “zipper” pattern of en echelon fractures crossing a fracture trace. Both the main and en echelon fractures contain chlorite-epidote mineralization. Top of photo is east.
TABLE 1. TERMINATION STYLES OF FRACTURE AND FAULT TRACES WITHIN THE BCFZ

<table>
<thead>
<tr>
<th>Type of trace</th>
<th>Termination style</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractures</td>
<td>Junction</td>
<td>70</td>
</tr>
<tr>
<td>(86 endpoints)</td>
<td>Covered</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Die at a tip</td>
<td>8</td>
</tr>
<tr>
<td>Faults</td>
<td>Junction</td>
<td>61</td>
</tr>
<tr>
<td>(64 endpoints)</td>
<td>Covered</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Die at a tip</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Step</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Horsetail splay</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Other*</td>
<td>2</td>
</tr>
</tbody>
</table>

* Endpoint location is uncertain.

In contrast to fracture traces, fault traces may terminate by a wide variety of styles (Fig. 5). Of the 32 fault traces mapped in the BCFZ, 14 of these traces terminate as junctions with other fault or fracture traces at both endpoints. The remaining 18 fault traces terminate as a combination of methods (i.e., a junction at one end and a stepover at the other end). Of these methods, disappearing beneath a covered area is the most common, as the traces of 10 faults terminate by this method on one end (Table 1). More fault traces terminate by dying out at a tip than by forming a splay structure. Despite outcrop-scale evidence for slip near the endpoints of many fault traces, splay fractures at the ends of fault traces are relatively rare. For example, the trace of fault 15 terminates at its southwestern end by dying out at a tip, yet a dike trace located 2 m from this endpoint of the fault trace is offset 23.5 cm (Plate 1). The width of a fault trace does not appear to increase or decrease as the trace approaches the endpoint with the exception of those fault traces that terminate at a tip or as a splay fracture. In such cases, the width of the fault trace decreases as the endpoint is approached.

The degree and type of mineralization present at the endpoints of a fault trace
varies without regard for the type of termination style. Typically, if chlorite-epidote mineralization exists along the trace of a fault, then such mineralization will extend to the endpoints if the fault trace terminates at a junction with another fault or fracture trace. In this case, chlorite-epidote mineralization is also present within the adjoining fault or fracture trace. In contrast, fault traces that terminate by dying out at a tip or by forming a horsetail splay structure may or may not have outcrop-scale evidence for chlorite-epidote mineralization, even if such mineralization is present along the fault trace. Within the BCFZ, in only two locations where a fault trace terminates by dying out at a tip (the southwestern end of fault 30 and the northeastern end of fault 33) was chlorite-epidote mineralization present at the tip of the fault trace. In the remaining six cases where a fault trace terminates at a tip, chlorite-epidote mineralization did not exist or was not visible on the outcrop-scale. Similarly, fault traces that terminate as a splay structure may or may not have chlorite-epidote mineralized splay fractures. But whereas most fault trace tips are not mineralized, a majority of the splay fractures contain outcrop-scale evidence for some chlorite-epidote mineralization. Thus the process of splay fracture development may promote the formation of chlorite-epidote mineralization.

Splay fractures branching away from the endpoint of a fault trace do not extend more than 20 cm in length. These fractures strike obliquely away from the fault trace at angles ranging from 10° to 60° in map view. The width of chlorite-epidote mineralization appears to be independent of both the length and the angle of the individual splay fractures. In addition, the amount of offset along the fault trace does not, in outcrop-scale, appear to affect the degree of mineralization present in the splay fractures. Absent from any of the chlorite-epidote mineralized splay fractures is outcrop-scale evidence for the presence of quartz within the fractures. All of the splay fractures curve into the host granodiorite in a direction consistent with left-
lateral slip along the fault trace.

Only four fault traces (faults 14, 15, 17, and 18) terminate as a stepover at one end. In this situation, any mineralization present within the fault trace is also present within the stepover and continues into the connecting fault trace.

Junctions between fracture and fault traces demonstrate a variety of physical characteristics. As previously mentioned, if a fracture or fault trace contains chlorite-epidote mineralization, then this mineralization is also present within the branching trace. This feature of junctions suggests that enough physical interaction between the connecting traces occurred to allow for substantial flow of fluids, and thus chlorite-epidote mineralization, to occur at these locations. Quartz mineralization is present at some junctions involving fault traces.

Junctions can be simply one fracture or fault trace branching off from another at a different angle, or can be a complex system of interacting subsidiary fractures and sites of intensive alteration and mineralization. Simple junctions are those in which one trace branches from another without subsidiary fracturing or extensive mineralization (Fig. 21a). The acute angle between the separating traces may range between 10° and 80°, with approximately half of all junctions having an acute angle between 30° and 50°. At some locations, splay fractures connecting the two separating traces exist within the acute angle (Fig. 21b). In this situation, the splay fractures are mineralized to a chlorite-epidote assemblage, but not to the same degree as the separating traces. These splay fractures are typically linear, and parallel to subparallel to one another. The size of the acute angle between the separating traces does not appear to affect either the linearity or parallelism of these splay fractures.

Where the junction becomes more complex, the physical features of the separating traces and splay fractures change. With increasing complexity, the splay fractures within the acute angle between the separating traces demonstrate a tendency
Figure 21. Characteristics of junctions. (a) Simple junction without splay fractures. Both fault traces contain chlorite-epidote mineralization. Top of photo is north. (b) Line drawing of a simple junction containing splay fractures. See Plate 1 for location. (c) Complex junction at point F14 showing splay and subsidiary fractures. All the fault and fracture traces contain chlorite-epidote mineralization, and are surrounded by altered granodiorite. Top of photo is west.
to curve. Eventually, the development of subsidiary fractures surrounding the junction begins and the degree of mineralization as well as the width of the splay fractures increase (Fig. 21c).

The amount of slip along a fault trace does not appear to affect the complexity of a junction. Some fault traces with relatively small amounts of slip have complex junctions along their traces, whereas other faults with substantial slip have simple junctions. Therefore, no correlation between fault slip and junction complexity is possible.

Possibly a junction becomes more complex as the number of fracture or fault traces emerging from the junction increases. Junctions at points E4 and E31 have features characteristic of a complex junction and have two fracture or fault traces branching off from a single trace. The widths of the branching traces are greatest at the junction and decrease as the traces continue away from the junction. Splay fracturing within the acute angles between the branching traces and subsidiary fracturing surrounding the junction location is widespread, with alteration of the surrounding granodiorite common. Chlorite-epidote mineralization within the separating traces at these junctions reveals distinctive episodical mineralization patterns and the mineralized material is easily broken off by hand.

Crossovers display the same characteristics as complex junctions (Fig. 22). Similar to complex junctions, the widths of the two intersecting traces increase at the crossover, only to decrease as the traces continue away from the crossover. Chlorite-epidote mineralization is pervasive within the intersecting traces as well as the subsidiary fractures. Splay fractures are common within the acute angles between the two intersecting traces, and subsidiary fractures are present within the obtuse angles. None of the splay or subsidiary fracture traces are linear. At all crossovers, alteration of the surrounding granodiorite is present along the intersecting traces as
Figure 22. Characteristics of a crossover between two fault traces. Traces contain chlorite-epidote mineralization, whereas the splay and subsidiary fractures may or may not contain such mineralization. Top of photo is north.

...well as the splay and subsidiary fractures. The width of this alteration zone increases at the actual intersection of the two traces in order to encompass the subsidiary fractures. The mineralized material within the intersecting traces is easily broken by hand and reveals episodic chlorite-epidote mineralization. Outcrop-scale evidence for episodic chlorite-epidote mineralization along the subsidiary fractures is absent. However, not every mineralized subsidiary fracture contains the same coloration, suggesting that mineralization within the subsidiary fractures did not occur simultaneously.

Steps are not common within the BCFZ. Where steps occur (Table 2), they are relatively simple structures. Steps branching from individual fracture or fault...
### TABLE 2. LOCATION OF STEPS WITHIN THE BCFZ

<table>
<thead>
<tr>
<th>Location</th>
<th>Step Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between points B17 and D12</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between point C4 and fracture trace</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between points C5 and C7</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between point C1 and fault 3</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between point B13 and fault 8</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between point F4 and fault 21</td>
<td>Left-stepping</td>
</tr>
<tr>
<td>Between points G5 and G6</td>
<td>Right-stepping</td>
</tr>
</tbody>
</table>

Traces strike obliquely from the trace at angles between 10° and 40° and are typically less than one meter in length. Chlorite-epidote mineralization is present within the step if such mineralization exists within the connecting fracture or fault traces. Alteration of the granodiorite surrounding a step is uncommon. Only one right step is present within the BCFZ (Table 2).

Stepovers are uncommon within the BCFZ. The two stepovers within the BCFZ are left-stepping and each connects two individual fault traces to one another (faults 14 to 15 and faults 17 to 18) (Plate 1). Chlorite-epidote mineralization within the fractures that form the stepover is common, but the thickness of the mineralized stepover fractures is the same as the interacting fault traces. Alteration of the surrounding granodiorite is present only if it exists along the interacting fault traces. Few splay fractures are present within the stepover structure and none of them have outcrop-scale evidence for chlorite-epidote mineralization. The granodiorite bounded by the stepover structure rests higher than the surrounding rock outside the stepover, making visual recognition of the stepover easy. The stepovers have overall lengths ranging from 1 to 2 m, and are less than 50 cm wide.

In summary, there is little correlation between fault termination styles, the complexity of junctions, crossovers, and stepovers, the amount of slip along a fault trace, and mineralization. The amount of offset along a fault trace does not appear to
influence how a fault terminates, nor the complexity of junctions, crossovers, or stepovers. The number of fracture and fault traces located at a linkage structure does appear to affect the physical features of these structures. Chlorite-epidote mineralization may or may not be present where a fault trace terminates, but is common at junctions, crossovers, and stepovers. The thickness of chlorite-epidote mineralization is independent of slip and complexity. Previous field investigations in the Bear Creek region documented that quartz mineralization is common within splay fractures, junctions, and stepovers (c.f., Segall and Pollard, 1980; Segall and Pollard, 1983b; Martel et al., 1988; Bürgmann and Pollard, 1994; Evans et al., 1996). This finding led Evans et al. (1996) to hypothesize that fluid flow at depth within a fault zone is restricted to linkage structures. The overall lack of quartz mineralization in these structures within the BCFZ suggests that this hypothesis may be incorrect. Instead, quartz mineralization within the BCFZ indicates that fluid flow at depth occurs primarily along fault surfaces and is not restricted to the linkage between them.

Thin-Section Analysis. Thin-sections were cut from all the rock samples taken from within the BCFZ except for sample BC9-96. Seventy-three thin-sections were made, of which eight are 2.5 x 4 cm in size and the remaining 55 are 4.5 x 7 cm in size. Generally, the thin-sections are oriented perpendicular to the fracture or fault surface, and parallel to the slip vector. Several thin-sections are oriented parallel to the fracture or fault surface, and perpendicular to the slip vector. From these thin-sections, microscopic features demonstrating the effects of deformation, hydrothermal mineralization, and alteration can be observed. Deformation, hydrothermal mineralization and alteration are different physical processes, which may or may not have occurred simultaneously along a fracture or fault trace. Thus the microscopic fabrics seen in thin-section may be a combination of both processes.
The term deformation zone is used here to denote that portion of a fracture or fault trace which has a characteristic microscopic fabric relative to other deformation zones within the trace. This deformation zone term does not indicate which physical process took place, only that one or more of these physical processes occurred at a particular time to form the fabrics seen in the zone.

The primary deformation process to have occurred within the individual faults of the BCFZ is cataclasitic flow: a brittle process that is achieved by the mechanical fragmentation of rocks, and subsequent sliding and rotation of these fragments with movement (Passchier and Trouw, 1996). As a result of cataclasitic flow, there may be a gradual or abrupt transition between the deformation zones and the undeformed host rock. Intracrystalline deformation, manifested by undulose extinction and dynamic recrystallization of quartz grains within both the deformation zones and the adjacent host rock, is also common. Biotite grains at the boundary between the host rock and the deformation zones are typically ductilely deformed with slip along the (0001) plane and altered to chlorite or epidote. Hydrothermal mineralization and alteration within deformation zones is manifested by the precipitation of minerals such as quartz, calcite, epidote, and chlorite. The precipitation of these minerals gives the deformation zones an overall cohesive fabric.

Evidence for episodic brittle fracturing, hydrothermal mineralization, and alteration is pervasive in all the rock samples removed from the BCFZ. Such evidence includes a range of cataclasitic fault-rock fabrics, such as the size and shape of the clasts, the clast-to-matrix ratio, the composition of the matrix, and the mineralization resulting from hydrogeologic flow. All of the thin-sections contain multiple deformation zones having different fabrics existing side-by-side to one another (Fig. 23). In some thin-sections, different deformation zones crosscut one another, indicating the order in which these zones formed relative to one another.
Figure 23. Multiple deformation zones within fault traces. Bz = breccia deformation zone, Cz = cataclasite deformation zone, Gz = gouge deformation zone, P = plagioclase grains, Q = quartz grains. Field of view for both microphotographs is 4 mm wide. (a) Sample BC14-96 under cross-polarized light. (b) Sample BC17-96 under cross-polarized light.
Furthermore, mineral fragments removed from the host rock during earlier fracturing events have been altered or reabsorbed by later mineralization episodes.

Three types of deformation zones, distinguished primarily by the clast-to-matrix ratio, are present in thin-section (Fig. 25). Breccia zones are deformation zones that contain more than 30% volume of angular clasts of the host rock separated by a fine-grained matrix. Breccia zones have primarily plagioclase and quartz grains with a large range of sizes and shapes. Calcite, chlorite, and epidote clasts are rare. Biotite and hornblende clasts are absent. Fabrics indicating dynamic recrystallization are absent, but quartz grains commonly have intracrystalline deformation fabrics. Breccia zones tend to be lighter in color than the other two types of deformation zones. Cataclasite zones contain less than 30% volume of angular clasts of the host rock separated by a fine-grained matrix. Cataclasite zones have a wider range of widths and smaller clasts sizes compared with breccia zones. In some cases, clasts are not present and the deformation zone is entirely matrix. Plagioclase grains, along with quartz grains having dynamic recrystallization and intracrystalline deformation fabrics, are the primary clasts within cataclasite zones. Small clasts of calcite are also present in cataclasite zones. Clasts of biotite, hornblende, chlorite, and epidote are absent. Cataclasite zones have a wide range of color, from light to dark, and may or may not have a foliated fabric. Finally, gouge zones are deformation zones having an iron-oxide matrix without clasts, a very dark appearance, and extremely thin widths. Gouge zones typically have a well-foliated fabric.

The presence of narrow, fault-bounded gouge zones, as well as the foliated fabrics within the gouge and cataclasite zones, provides some insight into the process of fault-rock development, brittle versus ductile deformation mechanisms, and the amount of slip required to produce the microscopic fabrics found within fracture and
Figure 24. Photomicrograph showing a breccia zone crosscutting a foliated cataclasite zone. Bz= breccia zone, Cz= cataclasite zone. Field of view is 3 mm wide. Sample BC21-96 under plane polarized light.

Figure 25. Types of deformation zones. Bz= breccia deformation zone, Cz= cataclasite deformation zone, Gz= gouge deformation zone, P= plagioclase grain, Q= quartz grain. Field of view is 4 mm wide. Sample BC17-96 under cross-polarized light.
fault traces. Experimental work by Yund et al. (1990) using samples of Westerly Granite produced an amorphous material within the granite samples which is similar in appearance to the gouge zones found in thin-section. This amorphous material resulted from extremely fine pulverizing of the crystalline particles rather than by melting due to frictional heating or crystal plastic processes (Yund et al., 1990). Once formed, the amorphous material continued to undergo comminution under brittle deformation conditions as the overall displacement increased, and the amount of amorphous material increased with increasing average shear strain (Yund et al., 1990). Feldspars were found to make up the bulk of the amorphous material (Yund et al., 1990), which may explain why quartz clasts outnumber the plagioclase clasts within the deformation zones present in the thin-sections.

Foliated fabrics, like those found within the gouge and cataclasite zones, are closely associated with ductile deformation mechanisms. As a result, researchers (e.g., Sibson, 1977; Wise et al., 1984) have suggested that brittle deformation processes produce only non-foliated fabrics. However, experiments dominated by brittle conditions and deformation mechanisms conducted by Chester et al. (1985) produced results that resembled naturally foliated fault gouge in sandstone. Thus cataclastic flow can lead to the flattening of mineral components and the generation of flow structures much the same way as in microscopically ductile deforming mylonites (Chester et al., 1985). This process is called brittle strain softening in this study. The experimental results of the Chester et al. (1985) and Yund et al. (1990) indicate that the development of both foliated and nonfoliated gouge zones, as well as foliated cataclasite zones, can occur during brittle deformation conditions. Furthermore, Means (1989) proposed that flow and brittle faulting can occur simultaneously, especially where slip is nonlinear. However, the presence or absence of foliation cannot be used solely to determine whether fault-rocks formed under
brittle shallow-crustal conditions or ductile deep-seated conditions (Chester et al., 1985; Means, 1989).

The overall fine-grained nature of the gouge and cataclasite zones is representative of a fault zone which has experienced tens of meters to kilometers of slip along its trace (e.g., Chester et al., 1993; Goddard, 1993; Goddard and Evans, 1995). However, the maximum amount of slip that has occurred along the trace of the BCFZ is no greater than ~2 m. The gouge zone-like material produced during the Yund et al. (1990) experiments formed in samples that had experienced 18.3 to 376 mm of total displacement, suggesting that fine-grained gouge and cataclasite zones can develop in fault zones that have experienced relatively small amounts of slip. Therefore, another process in addition to slip may be necessary to produce fine-grained gouge and cataclasite zones.

Fault gouge containing chlorite has a lower frictional strength than the host rock. The frictional coefficient of a gouge decreases from 0.75 to 0.43 as the percentage of chlorite and clay in the gouge increases (Shimamoto and Logan, 1981). Furthermore, stable sliding along a fault replaces stick-slip behavior once the gouge contains 25% chlorite (Shimamoto and Logan, 1981). The random distribution of chlorite-epidote mineralization within the faults in the study area, as well as deformation zones with different amounts of gouge, suggests that frictional strength and slip behavior varies within the BCFZ.

Crosscutting of individual deformation zones not only provides evidence for episodic fracturing and mineralization, but can be used to establish the order in which the deformation zones formed. Where crosscutting occurs, breccia zones consistently cut across cataclasite and gouge zones, and cataclasite zones cut across gouge zones (Fig. 24). In some cases, a breccia or cataclasite zone will surround a gouge zone (Fig. 23b) or split a gouge zone into several strands (Fig. 25). Breccia zones are not
cut by either cataclasite or gouge zones. Thus the crosscutting relationship between deformation zones suggests that the darker, extremely fine-grained gouge zones are oldest, whereas the lighter, coarse-grained breccia zones are the youngest.

Although the color of a deformation zone may indicate age, as with the gouge and breccia zones, such a technique cannot be used to establish the relative age of multiple cataclasite zones. In some thin-sections, clasts of a lighter-colored cataclasite zone are present within the matrix of a darker cataclasite zone (Fig. 26). Therefore, the color of a cataclasite zone is probably representative of the chemical composition of the hydrothermal fluid flowing through the fracture or fault trace rather than of the age of fracturing.

The distribution of deformation zones within fracture and fault traces comprising the BCFZ is not consistent. Whereas all three types of deformation zones may be in a thin-section, the presence of breccia zones is not as widespread as cataclasite and gouge zones. Cataclasite zones, having a wide range of possible fabrics, are the most common deformation zones in thin-section. The presence of a

![Figure 26. Clasts of one cataclasite zone with another. Field of view is 2 mm wide. Sample BC3-96 under crossed-polarized light.](image)
particular fabric characteristic of a hydrothermal mineralization or alteration episode is not restricted to a specific physical setting (i.e., calcite-dominated mineralization is not restricted to junctions between fault traces). The exception is quartz pockets resulting from precipitation from fluids are only present in samples taken from a fault trace. As for fracturing processes, samples having fabrics indicating brittle deformation are randomly distributed throughout the BCFZ, whereas samples containing fabrics resulting from ductile deformation are restricted to fault traces located in fracture network III.

Microscopic evidence for ductile deformation is present in samples BC13-96, BC15-96, and BC21-96, all of which were located within fracture network III. The first two samples were taken from the trace of fault 27, whereas BC21-96 was removed from the trace of fault 25. Samples BC13-96 and BC15-96 have distinctive mylonitic fabrics in thin-section (Fig. 27a). The presence of calcite grains and veins within the mylonite suggests that precipitation of calcite occurred during or shortly after ductile deformation. The mylonitic zones are separated from the host rock by either a cataclasite zone, a gouge zone, or both. Quartz clasts containing intracrystalline deformation and dynamic recrystallization fabrics are common within these deformation zones. All of the mylonitic zones are offset by microfaults (Fig. 27a). Clasts with mylonitic fabrics are present in the matrix of adjacent deformation zones (Fig. 27b), suggesting that ductile deformation occurred early during the formation of the BCFZ and was followed later by brittle deformation processes. In some thin-sections, hydrothermal mineralization is intermingled among the mylonite (Fig. 27c). Thin-section analysis cannot determine whether this intermingling occurred during ductile or brittle deformation episodes. However, the intermingled mineralization is often offset by the same microfaults that offset the mylonite,
Figure 27. Characteristics of mylonitic fabrics cut by brittle fabrics. Each photomicrograph was taken from sample BC15-96 under cross-polarized light. Field of view for all the photomicrographs is 4 mm wide. (a) Mylonitic fabric in ribboned quartz offset by microfaults. (b) Clasts within adjacent cataclasite zone containing reoriented mylonitic fabric in ribboned quartz. (c) Hydrothermal mineralization intermingled among mylonitic fabric.
suggesting that the majority of hydrothermal mineralization occurred before brittle deformation.

Only one sample was taken from the trace of a boundary fault. This sample, BC2-96, was removed from the southern boundary fault of the western simple fault zone between points G10 and G12 (Plate 1). In thin-section, the fault trace consists of several distinct cataclasite zones. These cataclasite zones tend to be very fine- to fine-grained, with few clasts of the host rock within the matrix. The cataclasite zones are separated from the host rock by a breccia zone on one side and a gouge zone on the other. However, the gouge zone is not continuous throughout the sample.

Two samples, BC11-96 and BC21-96, were collected from fault traces that are extensions of simple fault zone boundary faults. Sample BC11-96 was taken from the trace of fault 22, the southwestward extension of the northern boundary fault of the eastern simple fault zone (Plate 1). Thin-sections made of BC11-96 contain a quartz pocket resulting from the precipitation of quartz from a hydrothermal fluid. This quartz pocket is separated on both sides from the host rock by a cataclasite zone. Individual quartz grains within the quartz pocket have both intracrystalline deformation and dynamic recrystallization fabrics. Furthermore, intermingling of hydrothermal mineralization with the deformed quartz grains is common. Ductile deformation fabrics are absent within both the quartz pockets and the surrounding deformation zones. Sample BC21-96 was taken from the trace of fault 25, the northeastern extension of the southern boundary fault of the western simple fault zone (Plate 1). This sample consists of multiple deformation zones and lacks quartz pockets. The quartz clasts within the deformation zones have intracrystalline deformation and dynamic recrystallization fabrics. Both samples contain episodic hydrothermal mineralization, crosscutting of different deformation zones, and microfaulting (Fig. 24). Mylonitic fabrics are present within sample BC21-96,
indicating that fault 25 has experienced some localized ductile deformation.

Fabrics within thin-sections made from samples taken from junctions indicate that fluid interaction between individual fracture or fault traces was extensive and occurred either simultaneously with, or shortly after, brittle fracturing. All the thin-sections show episodic hydrothermal mineralization, alteration, the development of calcite-rich veining which cuts across the deformation zones and into the undeformed host rock, alteration of plagioclase and quartz clasts to zeolites, and the precipitation of calcite grains within the deformation zones. Crosscutting relationships are difficult to establish due to widespread overprinting of older fabrics by later mineralization episodes. Junctions between fracture and fault traces are not as complex in terms of brittle fracturing, hydrothermal mineralization, or alteration episodes as junctions between two fault traces. Surprisingly, the complexity of a junction at the outcrop-scale does not reflect the complexity of the junction at the microscopic-scale. Simple junctions at the outcrop-scale have the same degree of microscopic complexity as junctions with a complex appearance at the outcrop-scale.

Microfaults are widespread within the deformation zones in thin-section. Microfaults exist as either faults offsetting an individual clast within a deformation zone or as faults offsetting one or more deformation zones (Fig. 28). In some cases, microfaults impedes or redirects hydrothermal mineralization within a fracture or fault trace (Fig. 28), thereby influencing the flow of fluids along fracture and fault traces.

Evidence for the precipitation of zeolitic minerals is present within most of the thin-sections analyzed. These zeolites exist as discrete masses or as stringers within deformation zones (Fig. 29). In several cases, quartz and plagioclase clasts within deformation zones have been partially or completely altered to zeolites.

The outcrop-scale alteration of the host rock bordering the fracture and fault
Figure 28. Microfaults offsetting hydrothermal mineralization and deformation zones. Field of view for all the photomicrographs is 4 mm wide. Sample BC19-96 under: (a) cross-polarized light, and (b) plane polarized light. Sample BC15-96 under: (c) cross-polarized light, and (d) plane polarized light.
traces comprising the BCFZ is present in thin-section. In samples having this alteration, the plagioclase grains in the host rock have a cloudy, brownish appearance in both plain and cross-polarized light (Fig. 30). This alteration appears to be restricted to just the plagioclase grains, because quartz grains within the thin-sections lack this turbid appearance. Plagioclase feldspars are susceptible to the action of hydrothermal solution, and the cloudy, brownish appearance is often ascribed to hydrothermal activity (Deer et al., 1992). Whether this hydrothermal alteration occurred during the opening of the fracture trace, during brittle fracturing along the fault trace, or in conjunction with other physical processes is unknown. However, altered plagioclase clasts are widespread in deformation zones, suggesting that alteration of the plagioclase occurred prior to being removed from the host rock during brittle fracturing.

Dikes and Slip Distribution. In this portion of the BCFZ section, the location and physical characteristics of the dike traces within the BCFZ are described. A discussion of the slip distribution within the BCFZ is also given here.
Dike traces that have been cut by the entire width of the fault zone are listed, along with their offsets, in Table 3. All the dike traces in the BCFZ have been left-laterally offset. Within the BCFZ, the intersection of the dike traces with fault traces are sharp with no outcrop-scale evidence for smearing of the aplite during slip.

Fourteen aplite dike traces are cut by the BCFZ. Seven of these dikes cross the entire fault zone. The remaining dike traces only partially extend across the fault zone. All the dikes have traces striking northwest-southeast (Fig. 12e). The dip directions vary, with some dikes dipping to the southwest and others to the northeast. Like fracture and fault traces, dike traces commonly disappear beneath covered areas and may be located in the brecciated zones bounded by simple fault zones. As a result, following the trace of a dike is subjected to the same problems associated with following fracture and fault traces. Following dike traces across a fault zone is further complicated by the fact that dike trace widths may vary substantially along strike, making the matching of traces across even small covered areas difficult.

Dikes are important to the study of fault zones as they are the best outcrop-scale evidence for slip along a fault trace and within the fault zone as a whole. It is
TABLE 3. OFFSET OF DIKE TRACES THAT EXTEND ACROSS THE WIDTH OF THE BCFZ

<table>
<thead>
<tr>
<th>Dike</th>
<th>Fault</th>
<th>Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dike 1</td>
<td>Fault 3</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Fault 4</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Fault 11</td>
<td>190*</td>
</tr>
<tr>
<td></td>
<td>Total across BCFZ</td>
<td>282</td>
</tr>
<tr>
<td>Dike 2</td>
<td>Fault 3</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Fault 4</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Fault 11</td>
<td>170*</td>
</tr>
<tr>
<td></td>
<td>Total across BCFZ</td>
<td>262</td>
</tr>
<tr>
<td>Dike 3</td>
<td>Fault 9</td>
<td>60§</td>
</tr>
<tr>
<td></td>
<td>Fault 10</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Fault 18</td>
<td>160*</td>
</tr>
<tr>
<td></td>
<td>Fault 12</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Total across BCFZ</td>
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</tr>
<tr>
<td>Dike 8</td>
<td>Fault 27</td>
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</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Fault 26</td>
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<td></td>
<td>Fault 25</td>
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</tr>
<tr>
<td></td>
<td>Fault 31</td>
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<td></td>
<td>Fault 30</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Fault 28</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Total across BCFZ</td>
<td>530</td>
</tr>
<tr>
<td>Dike 9</td>
<td>Fault 27</td>
<td>122*</td>
</tr>
<tr>
<td></td>
<td>Fault 26</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Fault 25</td>
<td>250 - 105†</td>
</tr>
<tr>
<td></td>
<td>Fault 31</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Fault 33</td>
<td>30</td>
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<tr>
<td></td>
<td>Total across BCFZ</td>
<td>528</td>
</tr>
<tr>
<td>Dike 11</td>
<td>Fault 27</td>
<td>160</td>
</tr>
<tr>
<td>Dike 13</td>
<td>Western simple fault zone</td>
<td>180</td>
</tr>
<tr>
<td>Dike 14</td>
<td>Western simple fault zone</td>
<td>0</td>
</tr>
</tbody>
</table>

* Estimated value. Dike trace is partially covered.
§ Maximum value of offset.
† Maximum and minimum value of offset. See text for discussion.
the offset of a dike along a fracture trace that allows for the quick determination that the fracture is actually a fault. Furthermore, the offset of a dike along a fault trace gives a clear indication of the direction of slip on the fault. Dike offsets also permit the determination of the net slip on a fault trace, from which the slip gradients can be calculated. On a larger scale, dike offsets across a fault zone can be used to establish the nucleation and growth history of the fault zone.

The traces of dikes 1 and 2 are located near the eastern end of the BCFZ (Plate 1). Whereas dike 1 maintains a consistent 28 cm width along its trace, the width of the dike 2 trace varies from -28 to 80 cm between fault 11 and the covered area to the north. Both dikes are parallel to subparallel to each other along most of their length and are separated from each other by 1.2 to 4.6 m. However, portions of the trace of dike 2 are oriented differently than the general trend of both dikes 1 and 2. The different orientation of dike 2 might indicate that dike 2 is actually a composite of several separate dike traces.

The trace of fault 11 offsets both dikes 1 and 2 by approximately similar amounts: 190 cm for dike 1 and 170 cm for dike 2 (Table 3). These offset measurements are estimates because the traces of both dikes are covered at some locations along fault 11. Northward, both dike traces are offset by faults 3 and 4. Unlike fault 11, however, the intersections with these two fault traces are completely exposed, permitting exact measure of the offsets. The offset along the trace of fault 3 is approximately twice that of fault 4. No attitude measurements were available from the traces of dike 1 or 2.

It is difficult to trace dike 3 across the entire width of the BCFZ. In map view, the dike trace that is offset by the trace of fault 12 strikes in a more north-south direction than its projected continuation north of point C17 (Plate 1). From point C17, the dike trace strikes in the northwest-southeast direction typical of the dikes
within the fault zone. The change in dike trace direction may be the result of rotation about a vertical axis due to localized strain occurring within the host granodiorite between the fault traces. This suggestion is presented in detail in the Discussion. The width of this dike trace also increases as it extends northwestward across the fault zone. At point A20 on the trace of fault 12, the dike trace is 14 cm wide. At point B6, the continuation of the dike north of fault 12, the dike trace is 25 cm wide. Furthermore, the dike trace north from point C19 is 50 cm wide. Between points C17 and C18, the dike trace physically increases in width as the trace extends across the fault zone (Plate 1).

Dike 3 is offset at four locations along its trace (Table 3). The trace of fault 12 offsets the dike by 50 cm. Northwestward, no direct offset measurement was possible along fault 18 because the fault trace is beneath a covered area. However, projecting the dike trace across the covered area gives an estimated 160 cm of offset along fault 18. At point C18, the dike trace stops and does not continue northward to intersect with fault 10. But the dike trace is present within the granodiorite on the northern side of fault 10 at point C19 (Plate 1). Projecting the dike trace from point C18 to the trace of fault 10 gives an estimated offset of 52 cm. Finally, the offset of the dike trace between faults 1 and 9 is 60 cm. This offset is a maximum because the location of the dike trace between faults 1 and 9 is beneath the covered area located between the two fault traces. North of fault 1, the trace of dike 3 continues northwestward without any offsets along the four intersecting fracture traces (Plate 1). An attitude of 171°, 34°SW was taken on the trace of dike 3.

Dikes 4 and 5 have parallel traces separated by ~1 m (Plate 1). Both dike traces are offset by the trace of fault 15 and terminate at the trace of fault 18 to the northwest. There is no continuation of either dike north of fault 18. The trace of dike 4 has an attitude of 155°, 65°SW, whereas the attitude of dike 5 is 150°, 73°SW.
The widths of both dike traces are similar: 3 cm for dike 4, and 3.5 cm for dike 5. However, the offsets of these two dike traces by the same fault trace are dissimilar. Dike 4 is offset 29 cm, whereas dike 5 is offset 23.5 cm. The trace of fault 15 ends at a tip 1.9 m southwest of the dike 5 trace (Plate 1). Thus the decrease in the amount of offset between the two dikes along the same fault trace, as well as the nearby endpoint of the fault trace, suggests that slip along a fault plane may decrease as the edge of the fault plane is approached.

The trace of dike 6 is located at the western end of the eastern simple fault zone (Plate 1). This dike trace only crosses the trace of fault 22, which is the southwestward continuation of the northern boundary fault. The trace of dike 6 is only 3 cm wide and has an attitude of 354°, 26°NE. The offset of the dike trace along fault 22 is 44 cm. This dike trace continues southward and intersects the next fracture trace, but was not found continuing further southward. An unnumbered dike trace extends southward from the southern side of fault 23, only to disappear beneath a covered area and then reappears as an exposed dike trace south of fault 28. Although it appears that this dike trace is the continuation of dike 6 in map view (Plate 1), no outcrop-scale evidence exists to confirm that this dike trace joins with the trace of dike 6. The unfractured rock volume between the fracture trace in which dike 6 terminates against and fault 23 does not contain a visible dike trace. Furthermore, the southern dike trace has no measurable attitude, making direct correlation between this dike trace and dike 6 difficult. Thus the trace of dike 6 may or may not extend across the fault zone.

The trace of dike 7 begins at point F9 and extends northwestward to point E28, where it is offset by the trace of fault 24 (Plate 1). The offset along fault 23 is ~1.5 m, moving the dike trace to point E29. The dike trace continues northwestward from point E29 into the host granodiorite with an attitude of 165°, 49°SW. South of
point F9, the continuation of this dike trace could not be found. The trace of dike 7 has a width of 3 cm at point E29.

The trace of dike 8 extends across the entire width of the BCFZ (Plate 1). The strike of this dike trace varies from 145° to 153°. Only one dip measurement, 75° to the southwest, was obtained. At point F12, the width of the dike trace is 6.5 cm. The northwestern end of dike 8 crosses the fault step complex of fracture network III (Fig. 14). As a result, offsets on this dike trace vary considerably in this region, from 19 to 183 cm (Table 3). Continuing southeastward, the trace of dike 8 is offset 207 cm by the trace of fault 25 (Plate 1). From here, the amount of offset of dike 8 decreases as it crosses the traces of fault 31 (48 cm), fault 30 (27 cm), and fault 28 (20 cm) (Table 3).

Like the trace of dike 8, the trace of dike 9 extends across the entire width of the BCFZ (Plate 1). The strike of the dike 9 trace ranges from 142° to 145° and has a dip direction of 54°SW. The width of this dike trace is 4 cm at points E41 and F20. The trace of dike 9 does not extend across the fault step complex. The offset of dike 9 across fault 27 is 122 cm, 85 cm less than dike 8 (Table 3). But the offset along fault 27 for dike 9 is an estimate because the continuation of the dike trace north from fault 27 is beneath a covered area. Southeastward, the trace of dike 9 is offset 70 cm along fault 26. Southeast of fault 26, the dike trace continues until it intersects with the transfer fault located between points F1 and F23 (Plate 1). Southeast of this transfer fault, the trace of dike 9 disappears within the brecciated material between the transfer fault and fault 25. Projecting the dike trace to the north side of fault 25 gives an estimated offset of 250 cm along fault 25. The distance between point F1 and the location of the dike 9 trace south of fault 25 is 105 cm. Thus the actual offset of the dike 9 trace by the trace of fault 25 is between 105 and 250 cm. The trace of dike 9 is probably offset by the trace of the transfer fault, but
the brecciated condition of the rock south of the transfer fault makes determining the offset along the trace of the transfer fault impossible. South of fault 25, the trace of dike 9 continues into fracture network IV with decreasing offset amounts. Fault 31 offsets the dike trace 66 cm, whereas fault 33 offsets the dike 20 cm. South of fault 33, the trace of dike 9 continues within the host granodiorite.

The trace of dike 10 only crosses the southern boundary fault of the western simple fault zone (Plate 1). This dike trace has an attitude of 294°, 33°NE and a width of 2 cm. The boundary fault offsets the dike trace 38 cm. Continuation of this trace northwestward is problematic as the trace disappears beneath a covered area. Northwest of the covered area, there is no evidence for continuation of this dike, either within the rock bounded by the two boundary faults or in the host granodiorite north of the western simple fault zone.

In the same locality of dike 10 is dike 11, which I consider to extend across the entire BCFZ. The trace of this dike is ~14 cm wide and has an attitude of 5°, 34°SE. The exact location of portions of dike 11 is problematic (Plate 1). The dike trace is present within the host granodiorite south of the southern boundary fault. Before reaching the boundary fault, however, the dike trace disappears beneath the same covered area as the trace of dike 10. The trace of dike 11 reappears on the northern side of the transfer fault connecting points G13 and G18 (Plate 1). Between this transfer fault and the northern boundary fault, the trace of dike 11 is well-exposed within the rock. North of the boundary fault, however, the dike trace is not present on the rock surface. At point G15, the dike trace reappears on the north side of fault 27 and continues into the host granodiorite (Plate 1). What happened to the dike trace between the northern boundary fault and the trace of fault 27 is unknown. If the trace of dike 11 is projected from the intersection with the northern boundary fault to the trace of fault 27, an estimated offset of 1.6 m is obtained. In contrast, the
trace of dike 11 does not appear to have been offset by the southern boundary fault, which is inconsistent when compared to dikes 10 and 13. Possibly, the location of the dike 11 trace south of the southern boundary fault into the host granodiorite as mapped is incorrect. This, combined with the fact that the intersection between the trace of dike 11 and the southern boundary fault is covered, makes the measurement of any offset by the southern boundary fault speculative. While problems exist with portions of dike 11, the width of the exposed parts of the dike trace is consistent across the width of the entire fault zone.

The trace of dike 12 is only exposed north of the western simple fault zone (Plate 1). From point G8 on the northern boundary fault, this dike trace extends northwestward with an attitude of 331°, 14°NE and has a width of ~20 cm. There is no evidence for the continuation of this dike trace southeastward across the western simple fault zone. The dike trace is not offset by the trace of the fracture connecting point G22 to point G23.

Dike 13 has the only trace which unequivocally crosses the western simple fault zone (Plate 1). This dike trace is ~2.5 cm wide and has an attitude of 260°, 81°SE in the host granodiorite south of the simple fault zone. At point G10, the dike trace intersects the southern boundary fault (Plate 1). Between the northern and southern boundary faults, the location of the dike trace is not visible within the brecciated rock. At point G6 on the northern boundary fault, the dike trace reappears and acts as a right step along the trace of the northern boundary fault (Fig. 13). Projecting the dike trace from point G10 gives an offset of 1.8 m across the western simple fault zone. North of the simple fault zone, the trace of dike 13 continues within the host granodiorite with a strike of 261°.

Beyond the western exposure of the BCFZ is the trace of dike 14 (Plate 1). This dike trace does not actually cross the exposed portion of the BCFZ. Instead,
this dike intersects the southern boundary fault at point G3 with an attitude of 292°, 61°NW. From here, the dike trace disappears beneath the covered area and emerges at point G1, which is not located within the BCFZ (Plate 1). From point G1, the dike trace continues into the host granodiorite with an attitude of 285°, 64°NW. Projecting this dike trace across the covered area gives an offset of zero. Assuming that the BCFZ terminates beneath this covered area, the lack of an offset suggests that the total slip along the fault zone decreases to zero beneath the covered area.

The offset of dike traces within the BCFZ reveals an interesting characteristic concerning the slip distribution along individual fault traces (Fig. 31). Each of these faults were selected based on the following criteria: (1) each trace terminates at a tip or as a horsetail splay structure; (2) each trace offsets one or more dike traces; and (3) each trace does not interact with another fracture or fault trace between the endpoint and the dike trace(s). No continuation of the displacement-length profiles beyond the dike farthest from the endpoint is shown because the other endpoint is either a junction, a stepover, or beneath a covered area, thereby violating criterion (1). Each displacement-length profile shows that the slip amount increases rapidly with gradients ranging from 1/1.5 to ~1/15 from the endpoint of the fault trace (Fig. 31). In the case of fault 15, the displacement gradient decreases to 1/18 between the two dike offsets.

Overall, offset dike traces across individual faults within the BCFZ have an irregular distribution along the trace of the fault zone (Fig. 32a). Most of the offsets cluster between 20 and 70 cm, but offsets between 120 and 250 cm are also present near the northeastern and southwestern ends of the fault zone (Fig. 32a). Faults with large offsets (> 120 cm) are primarily restricted to the southwestern end of the BCFZ. From Figure 32a, the cumulative displacement-length profile shown in Figure 32b was constructed for the entire BCFZ. The debate whether or not the trace of dike 6
Figure 31. Displacement-length profiles of fault traces with offsets near one endpoint. All four profiles are the same scale. Faults 15, 30, and 33 terminate at a tip, whereas fault 28 terminates as a horsetail splay. Each profile has a steep displacement gradients near the endpoint of the fault traces. Continuation of the profiles away from the right-most offsets are not shown because no offsets are present between these points and where the fault terminates as a junction, stepover, or beneath a covered area.
Figure 32. Displacement-length profile for the BCFZ. (a) Distribution of dike offsets across individual faults along the trace of the fault zone. (b) Displacement-length profile based on the cumulative offsets of those dike traces that cross the fault zone. The resulting profile has an irregular shape and steep displacement gradients at both endpoints. Error bars indicate that the exact endpoints of the fault zone are unknown. The cumulative offset of dike 6 is included on the profile. See text for discussion.
crosses the fault zone affects the cumulative displacement-length profile. Therefore, the displacement-length profile shown in Figure 32b includes both possibilities. The displacement-length profile has an irregular shape and steep displacement gradients (~1/6 and ~1/3) at both endpoints, similar to the fault traces in Figure 31. The highest point on the displacement-length profile coincides with fracture network III, between the two simple fault zones. Interestingly, the amount of slip along the boundary faults defining the simple fault zones accommodate only a small portion (~8 to 10%) of the total offset within the BCFZ (Table 3). The implications of an irregular displacement-length profile on fault-growth modeling are presented in the Comparison and Discussion sections.

**Lower Camp Fault Zone**

The Lower Camp Fault Zone (LCFZ) is the mid-sized fault zone discussed in this study. Unlike the BCFZ, the LCFZ does not contain any simple fault zones nor do the fracture and fault traces form fracture networks. The LCFZ is 300 m north of the BCFZ, extends in a N73°E direction, and is ~120 m long. The LCFZ is 8 m wide at its western end and tapers down in width to 1 m at the eastern end. Plate 3 is a map view of the LCFZ showing the overall geometry of the fault zone.

The trace of the LCFZ transverses a topographically gentle bowl-shaped region (Fig. 33). The western end of the LCFZ is located at the edge of an outcrop of the host Lake Edison Granodiorite. Starting at the western end, the LCFZ decreases in elevation until reaching a low point at the approximate center of the fault zone trace. From here, the elevation increases as the trace of the LCFZ continues northeastward. Eventually, the trace of the LCFZ terminates by intersecting with a simple fault zone. Between its two ends, the trace of the LCFZ extends over a region of alternating covered areas and exposed granodiorite with an
Figure 33. Lower Camp Fault Zone. (a) View westward from the fault step complex (point K30) of the gentle vertical relief along the fault zone. (b) View eastward from the fault step complex. The vertical relief decreases within the bowl area, only to increase as the eastern end of the fault zone is approached.
overall vertical relief of \(~10\) m.

The precise location of the western end of the LCFZ is difficult to determine because a covered area \(\sim 12\) m wide exists between the western edge of the fault zone and the host granodiorite to the west. West of this covered area, several fracture and fault traces are present in the outcrop, but it is not possible to match the projections of these traces with the traces comprising the LCFZ east of the covered area. Thus the western end of the LCFZ was inferred to lie beneath the covered area (Plate 3).

The eastern end of the LCFZ is next to a possible simple fault zone that is younger than, and unrelated to, the LCFZ. Field investigation established the existence of two boundary faults on either side of a volume of broken pieces of the host granodiorite, yet neither boundary fault is well-developed. In addition, this simple fault zone does not continue very far in either direction. The eastern end of this simple fault zone simply terminates without splay fracturing or branching off of separate fault traces. In the westward direction, the simple fault zone bends to the south and disappears beneath an area covered by soil and boulders. No continuation of the simple fault zone beyond this covered area is present. The existence of this simple fault zone is important as several fault traces branching away from the northern boundary fault offset fault traces within the LCFZ.

The control point for the LCFZ is labelled KO and is \(\sim 13\) m northeast of the western end of the fault zone. The lowest elevation within the LCFZ is at point L17, which has an elevation of \(-6.74\) m relative to KO. West of KO, L2 is the highest point with an elevation of 3.67 m relative to the control point. East of KO, point M23 is the highest location with an elevation of 3.27 m relative to the control point.

The fractures and faults that constitute the LCFZ form parallel to subparallel, non-coplanar traces. Obliquely-striking transfer fractures or faults between individual traces are rare. As a result, the fractures and faults comprising the LCFZ
cannot be grouped into fracture networks. The lack of transfer fractures or faults reflects the relatively early stage of fault zone development within the LCFZ. Interaction between the individual traces is accomplished primarily by steps. A small fault step complex connecting two individual fault traces together is located within the LCFZ. No slickenlines are exposed on any of the fault traces within the LCFZ. As with the BCFZ, outcrop-scale evidence for joints within the LCFZ is absent.

Ten aplite dike traces are cut by the LCFZ. All of these dike traces have been offset left-laterally. However, the fault traces at the eastern end of the fault zone have been offset both left- and right-laterally by fault traces originating from the simple fault zone located nearby. One left-laterally offset mafic inclusion is present within the LCFZ.

The following discussion of the LCFZ begins by describing the geometry of the fracture and fault traces which comprise the fault zone. Then the characteristics of the individual fractures and faults, such as their physical features and degree of mineralization, are described. This is followed by the various termination styles, as well as the characteristics of junctions, steps, and stepovers. A description of the geometry and physical characteristics of the fault step complex is presented next. Finally, a description of the dike traces, as well as a discussion of the slip distribution along the LCFZ, is given.

**Fault Zone Geometry.** The geometry of the LCFZ is made up of a series of parallel to subparallel, non-coplanar fracture and fault traces that strike in the general direction of the fault zone (Fig. 34a). Individual traces either terminate along the outcrop, beneath a covered area, or step to connect with another fracture or fault trace. Few junctions exist within this fault zone and the resulting branching traces are of short extent. Transfer fractures and crossovers are absent within the LCFZ.

Eleven fault and four fracture traces are present within the LCFZ, as well as
Figure 34. Equal-area stereograms of the fractures, faults, and dikes within the LCFZ. All stereograms are lower-hemisphere projections. (a) Poles of fracture and fault traces except for those comprising the fault step complex. The general orientation is similar to those within the BCFZ (Fig. 12a). (b) Poles of fracture traces that comprise the fault step complex. The splay and secondary fractures plot in different quadrants. (c) Poles of dike traces. The orientation of the dikes within the LCFZ is variable. (d) Poles of the interconnecting traces comprising the palm tree structure located along the trace of fault 2. Traces are approximately orientated north-to-south with dips to the west.
the fracture traces comprising the fault step complex (Plate 3). Nine younger fault traces originate from the simple fault zone located near the eastern end of the LCFZ. These nine younger fault traces are referred to in this study as subsidiary faults. For the following discussion, each of the eleven fault and four fracture traces are assigned a number and the geometric description of these traces begins in the northwest corner of the fault zone and continues in a south and east direction. Similarly, each dike trace is assigned a number and is described from west to east.

The trace of fracture 1 begins at the western end of the LCFZ, 4.2 m southwest of point K1 (Plate 3). This trace extends northeastward across the outcrop, crossing the trace of dike 1, and disappears beneath the covered area 1 m northeast of point K1. The trace of dike 1 is not offset. No northeastward continuation of this fracture trace beyond the covered area is present.

The trace of fault 1 emerges from beneath a covered area at point K17 (Plate 3). No southwestward continuation of this fault trace beyond the covered area exists. Northeastward, the trace of fault 1 extends across the outcrop to point K20, where it disappears beneath another covered area. At point K19, this fault trace offsets the trace of dike 6 by 19 cm (Plate 3). Approximately 1.5 m northeast of point K19, the trace of fault 1 offsets a mafic inclusion 12 cm. An attitude of 55°, 84°SE was taken from this fault trace at point K20. Northeast of point K20, the trace of fault 1 either continues to point L5, intersects with the trace of fault 3 beneath a covered area, or terminates beneath the covered area (Plate 3).

South and parallel to the trace of fracture 1 is the trace of fault 2. This fault trace emerges from the covered area southwest of point K2 and extends northeastward to the stepover between points K22 and K23 (Plate 3). At point K2, a fracture trace branches off from a junction with the trace of fault 2 and extends westward into the covered area. The trace of fault 2 offsets the trace of dike 1 by 27
cm at point K3 before disappearing and reappearing from beneath three covered areas. The trace of dike 6 is offset 20 cm at point K22. Northeast of point K22, the trace of fault 2 enters a stepover structure (Plate 3). The stepover is to the left and connects this fault trace to the trace of fault 3. Attitudes along this fault trace vary from 55°, 86°SE at point K2, 66°, 89°SE at point K4, and 59°, 78°SE at point K5.

Continuing northeastward from the stepover, the trace of fault 3 extends across the outcrop to point K24 (Plate 3). At this point, the fault trace disappears beneath the same covered area as the trace of fault 1. The trace of fault 3 appears to emerge from the covered area at point L5, but it is difficult to confirm whether it is the trace of fault 1 or fault 3 that actually emerges at point L5. Evidence for a junction between the two fault traces beneath the covered area is absent, nor does a second fault trace emerge from the covered area near point L5. Thus this study suggests that either the two fault traces join together beneath the covered area, or that one of the fault traces terminates beneath the covered area. If the second scenario is correct, which fault trace terminates beneath the covered area is not determinable from field observations. As a result, the trace of fault 3 was arbitrarily chosen as the fault trace that continues northeastward from point L5.

From point L5, the trace of fault 3 continues northeastward to point L8, where it disappears beneath another covered area (Plate 3). The fault trace does not appear to continue beyond this covered area. At point L17, the trace of fault 3 offsets the trace of dike 7 by 12 cm. An attitude of 58°, 82°SE was taken from the fault trace at point L6.

The trace of fault 4 emerges from beneath a covered area at a point 60 cm southwest of point K6 and continues northeastward to point L4 (Plate 3). Attitudes along this fault trace vary from 56°, 71°SE at point K6, 63°, 83°SE at point K9, and 57°, 81°SE between points K10 and K11. At point K7, the trace of dike 1 intersects
this fault trace, but both the dike and fault traces disappear beneath a covered area northeast of this point. Thus an offset measurement of the dike trace by the trace of fault 4 is not obtainable. Northeastward, the trace of fault 4 reappears from beneath the covered area and offsets the intersecting trace of dike 2 by 24 cm at point K8 (Plate 3). At point K10, the trace of fault 4 crosses several dike traces (Fig. 35). South of the fault trace is a covered area which hides the traces of dikes 3 and 4, making exact offset measurements along the fault trace difficult. At point K10, the trace of fault 4 offsets the trace of dike 3 an estimated 13 cm. To the northeast, projecting the trace of dike 4 so that it intersects the trace of fault 4 gives an estimated offset of 20 cm. Parallel to the trace of dike 4 is the trace of dike 5, which is exposed along both sides of the fault trace (Plate 3). The trace of fault 4 offsets the trace of this dike 26 cm. At point L4, the trace of fault 4 terminates by forming a

Figure 35. Offset of dike traces along the trace of fault 4 at point K10. See Figure 44 for a displacement-length profile of the fault trace at this point. Top of photo is south.
horsetail splay structure.

The trace of fault 5 emerges from beneath a covered area at point L2, along the western edge of the LCFZ (Plate 3). From this point, the fault trace extends northeastward through point L1 and disappears beneath another covered area, only to reappear at point K16. Whether the trace between points L2 and K16 is actually a fault trace is uncertain, as no slip indicators are present within the outcrop to verify slip along the trace. However, the attitude along this trace taken at point L1 measures 51°, 77°SE, within 3° for both the strike and dip obtained from the fault trace at point K15. Therefore, this portion of the trace is considered to be a fault. At point K16, the trace of fault 5 continues to point K15, where the trace of dike 2 is offset 6 cm (Plate 3). An attitude of 54°, 80°SE was obtained at point K15. The trace of fault 5 terminates at point K14 where a left step, fracture trace 2, connects the trace of fault 5 with the trace of fault 6 at point K13.

Northeast of point K13, the trace of fault 6 offsets the trace of dike 4 by 6 cm. Approximately 40 cm northeast of point K13, the trace of dike 5 is offset 10 cm by this fault trace (Plate 3). An attitude of 63°, 82°SE was taken from the fault trace at point K12. At point K25, the trace of fault 6 emerges from beneath a covered area and continues towards point K28, where the trace disappears again beneath a covered area. Between these two points the trace of fault 6 offsets the trace of dike 6 by 40 cm at point K27 (Plate 3). The fault has attitudes of 65°, 83°SE at a point 1.3 m northeast of K25 and 59°, 82°SE at point K28. Projecting the trace of fault 6 northeastward across the covered area places the fault trace at point K29. At this point, the fault trace has an attitude of 54°, 82°SE and continues northeastward as the southern boundary of the fault step complex (Plate 3). The trace of fault 6 terminates at point K33 by dying out at a tip.

The trace of fracture 3 begins at a junction along the trace of fault 6 northeast
of point K13 (Plate 3). This trace is a transfer fracture between the traces of faults 4 and 6. The trace of fracture 3 intersects the trace of fault 4 at a junction 1.5 m northeast of point K10. This fracture trace crosses the trace of dike 5, but does not offset it.

The trace of fault 7 begins at point K30, the northwestern corner of the fault step complex (Plate 3). Between points K30 and K31, this fault trace is the northern boundary of the fault step complex. From point K31, the trace of fault 7 extends to and beneath the covered area northeast of point K34. Between points K31 and K34, this fault trace has an attitude of 52°, 82°SE. Reappearing from beneath the covered area at point L9, the trace of fault 7 extends for only ~1 m, where it disappears beneath another covered area (Plate 3). This fault trace does not continue beyond the covered area.

Approximately 40 cm northeast of point L9, a left step branches away from a junction on the trace of fault 7 and extends to point L10 where a connection with the trace of fault 8 is made (Plate 3). Point L10 locates the beginning of the trace of fault 8, which continues northeastward beneath a covered area. Between points L10 and L12, this fault trace is only exposed along a small length of outcrop at point L11, with an attitude of 47°, 75°SE (Plate 3). At point L12, the trace of fault 8 reappears and continues across the outcrop to point L14. At point L13, the intersecting trace of dike 8 is offset 23 cm. An attitude of 66°, 80°SE was taken from the trace of fault 8 at point L14.

The trace of fault 8 reappears from beneath the covered area northeast of point L14 at point L16. This fault trace continues northeastward, with an attitude of 55°, 87°SE at point L17, to point L19 (Plate 3). At point L19, the trace of this fault disappears beneath a covered area. Projecting this fault trace across the covered area matches a horsetail splay structure with splay fractures that curve to the north. South
of the horsetail splay is the trace of fault 9, which emerges from beneath the covered area at point L20 (Plate 3). The presence of a horsetail splay aligning with the projection of the trace of fault 8, along with the northeastward extension of a separate fault trace, suggests that the trace of fault 8 intersects the trace of fault 9 beneath this covered area.

Parallel to the trace of fault 8 between points L12 and L14 is the trace of fracture 4. This fracture trace emerges from a covered area 1.1 m southwest of point L15 and extends northeastward for \(-2.9\) m until disappearing beneath another covered area (Plate 3). Along the outcrop surface, this fracture trace intersects, but does not offset, the trace of dike 8 at point L15. An attitude of 58°, 73°SE was taken at point L15.

The first exposure of the fault 9 trace occurs at point L20 (Plate 3). An attitude of 65°, 82°SE was taken on this fault trace at point L21. In addition, this fault trace offsets the trace of dike 9 by 18 cm at this point. Northeast of point L21, the trace of fault 9 continues with a straight trend until point L22, where it bends to the left and continues to point L23 (Plate 3). An attitude of 62°, 84°SE was taken at point L23. From point L23, this fault trace continues until disappearing beneath a covered area northeast of point L23B. The trace of fault 9 reappears at point L24.

From point L24, the trace of fault 9 continues northeastward, disappearing and reappearing from beneath three covered areas, to eventually terminate at point M24 (Plate 3). An attitude of 77°, 80°SE was taken on the fault trace at point L24. Further northeastward, the attitude changes to 82°, 77°SE at a point 1.7 m northeast of point L25. The trace of dike 10 is offset along the fault trace 19 cm at point M17.

The first intersection between the trace of fault 9 and a subsidiary fault originating from the simple fault zone occurs at point M21 (Plate 3). At this point, the trace of fault 9 is right-laterally offset 1.5 cm. A right-lateral offset of 3.5 cm on
the trace of fault 9 also occurs at point M22. Northeastward, between points M22 and M23, this fault trace is again right-laterally offset by five separate subsidiary faults: 8 mm, 2 cm, 50 mm, 90 mm, and 2.9 cm (Plate 3). At point M23, the trace of fault 9 is left-laterally offset 2 cm. The endpoint of the fault 9 trace is at point M24. Here, the fault trace is right-laterally offset 8.5 cm (Plate 3). Evidence for the continuation of the fault 9 trace east of the subsidiary fault is absent.

The trace of fault 10 is parallel to, and north of, the fault 9 trace. This fault trace emerges from beneath a covered area southwest of point M7 and extends to point M20 (Plate 3). The trace of dike 10 is offset 2 cm at point M16. At point M19, the westernmost subsidiary fault branching from the simple fault zone right-laterally offsets the trace of fault 10 by 2 cm. The trace of fault 10 terminates at point M20 by dying out at a tip.

South and subparallel to the traces of faults 9 and 10 is the trace of fault 11 (Plate 3). This fault trace begins at point M2 as simply a tip on the outcrop. Northeastward, the trace of fault 11 disappears and reappears from beneath three covered areas and offsets the trace of dike 10 by 9 cm at point M18. The trace of fault 11 does not intersect the westernmost subsidiary fault, which offsets the traces of faults 9 and 10. However, the trace of fault 11 terminates at an intersection with a subsidiary fault at point M25 (Plate 3). No continuation of this fault trace exists east of the subsidiary fault, suggesting that the trace either disappears within the simple fault zone, or that it developed after the formation of the subsidiary fault and did not extend beyond the intersection.

Ten splay fractures make up the traces within the fault step complex. The discussion of their geometry is included below in the section describing the fault step complex.

Nine subsidiary fault traces originating from the simple fault zone south of
the eastern end of the LCFZ intersect and offset three fault traces comprising the LCFZ (see detailed drawing in Plate 3). These subsidiary faults have traces with strikes ranging between 324° and 11°. A dip direction of 73°SE was taken on the trace of one of these subsidiary faults. With the exception of the easternmost subsidiary fault trace, the exact intersection of these subsidiary fault traces with the northern boundary fault of the simple fault zone could not be established.

**Individual Fractures and Faults.** This portion of the LCFZ section describes the physical characteristics of the individual fracture and fault traces comprising the LCFZ. Such characteristics include their appearance, degree of mineralization, and the alteration of the surrounding rock. In addition, the characteristics of the subsidiary faults branching from the simple fault zone beyond the eastern end of the LCFZ are also discussed.

All of the fracture and fault traces within the LCFZ are straight and linear. Individual traces range from one to tens of meters in length and have widths ranging between 1 and 15 mm, with the average width being ~5 mm. As with the BCFZ, the width of an individual fracture or fault trace is not consistent along the length of the trace. However, the width does not vary as much along the length of the traces within the LCFZ as it does along the traces within the BCFZ. The margins of the traces are consistently sharp, juxtaposing unfractured and unmineralized granodiorite next the the highly altered material within the trace.

The spacing between parallel to subparallel fracture and fault traces ranges from 25 cm to ~3.5 m. Figure 36 is a histogram of 32 spacing measurements taken from within the LCFZ. As with the BCFZ, no general pattern for the distance between traces exists. Unlike the BCFZ, 50% of the spacing measurements are less than 1 m (Fig. 36).

The degree of mineralization within the trace of a fracture or fault varies
Figure 36. Histogram of the distances between parallel to subparallel fracture and fault traces in the LCFZ. Thirty-two spacing measurements were obtained from within the fault zone, of which half are less than 1 m. See Figure 15 for an explanation of how this histogram was constructed.

along the length of the trace. Whereas no consistent pattern as to the width, composition, or location of mineralization along any one particular trace exists, the traces within the LCFZ have less variation of these features of mineralization than those traces comprising the BCFZ. Chlorite-epidote mineralization is pervasive within the fractures and faults comprising the LCFZ. In contrast, the presence of quartz mineralization is rare. Those locations where quartz is present are always along a fault trace. In vertical exposures, chlorite-epidote mineralization is common, whereas quartz mineralization is absent.

Fault traces in which quartz pockets are present tend to be wide. As the trace extends away from the quartz pocket, the width of the trace decreases. For example, at point M6 along the trace of fault 11, the quartz pocket is 2 cm wide (Fig. 37). As
the fault trace continues away from the quartz pocket, the width of both the quartz pocket and the fault trace decreases until only chlorite-epidote mineralization remains within the fault trace. Once this point is reached, the trace of fault 11 continues outward with a relatively consistent width. Within the LCFZ, quartz pockets are always surrounded by a chlorite-epidote rim. Pockets of chlorite-epidote mineralization also exist along traces of fractures and faults within the LCFZ. At these locations, the widths of these pockets are larger than the trace extending away from the pocket. At point L26, the width of a chlorite-epidote pocket is 7 mm, whereas the fault trace itself is only 2 to 3 mm wide southwest of the pocket (northeast of the pocket, this trace disappears beneath a covered area). It takes 12 cm for this chlorite-epidote pocket to taper down to the 2 to 3 mm width of the fault trace. At all locations where a chlorite-epidote pocket was present, the trace continuing away from the pocket contained outcrop-scale evidence for chlorite-epidote mineralization.

Figure 37. Quartz pocket along the trace of fault 11. Pink dot locates point M6. Top of photo is south.
The chlorite-epidote mineralization within the trace of fault 6 undergoes a substantial increase in width where this fault trace intersects the trace of dike 6 (point K27). The greatest offset along a fault trace within the LCFZ occurs at this location, suggesting that the increase in fault trace width and chlorite-epidote mineralization is related to the amount of offset. Points L22 and K26 (not located on Plate 3, but between points K25 and K27) are locations where increases in the fault trace width, the amount of chlorite-epidote mineralization, and the extent of altered granodiorite surrounding the fault trace occurs. However, both of these locations lack evidence for slip. Why an increase in fault trace width, mineralization, and surrounding altered granodiorite occurs at these two locations is unknown.

The episodic chlorite-epidote mineralization that occurred within the BCFZ also occurred within the fracture and fault traces comprising the LCFZ. Evidence for such episodic mineralization, however, is not as widespread and is primarily restricted to locations where the traces interact between one another or intersect a dike trace. At those locations where episodic mineralization exists, only two distinct mineralization episodes are present. In addition, outcrop-scale evidence for these episodes crosscutting one another is absent.

Zones of altered granodiorite surrounding the traces of fractures and faults comprising the BCFZ are also present within the LCFZ. The alteration zones do not surround the entire trace of a fracture or fault, and are noticeably absent at the endpoint of a fault trace if the trace terminates by simply dying out at a tip. The altered zone extends up to ~2 cm away from the trace into the host granodiorite except where the width of a fracture or fault trace increases with increasing mineralization, and within the fault step complex. The raised, rib-like appearance associated with this alteration, discussed in the description section of the BCFZ, is absent within the LCFZ. Instead, the height of the alteration zones surrounding the
fracture or fault traces is the same as the unaltered granodiorite.

The vertical plane of an individual fracture or fault trace is exposed only where a fracture or fault trace disappears beneath a covered area which is topographically lower than the outcrop. With the exception of the one location discussed below, all of these vertical surfaces expose only the fracture or fault trace. Subsidiary fractures, similar to those in the vertical exposures within the BCFZ, are absent. If the fracture or fault trace contains chlorite-epidote mineralization along its trace on the outcrop, such mineralization was present within the vertical plane of the trace. The width of the trace in the vertical plane was consistent with the outcrop exposure and did not change with depth. Quartz mineralization within the traces exposed on the vertical plane is absent.

At one location within the LCFZ, a fault trace is exposed in three dimensions. Where the trace of fault 2 disappears beneath a covered area, 50 cm northeast of point K3, the granodiorite bordering the southern edge of the fault trace is missing. Thus two vertical sides as well as the horizontal outcrop surface of the fault trace are exposed (Fig. 38). At this location, the fault trace forms a palm tree structure similar to that described by Woodcock and Fisher (1986). This structure consists of a fault trace branching away from the main fault trace and curving to the north, only to change direction and curve with a northeastward trend. Between the main fault trace and this branching trace are a series of curved traces connecting the two diverging traces to one another. Some of these curved fault traces interact with each other at depth. The attitudes of these interconnecting traces range between 169°, 74°SW and 201°, 89°NW (Fig. 34d). The branching trace, as well as the interconnecting traces, contains chlorite-epidote mineralization on their exposed fault surfaces.

The physical appearance of the nine subsidiary faults originating from the simple fault zone near the eastern end of the LCFZ does not reveal any evidence for
Figure 38. Palm tree structure along the trace of fault 2. (a) Top of photo is north. (b) Top of photo is east.
their origin or connectivity. How these fault traces connect with the simple fault zone is somewhat problematic, as their continuation into the simple fault zone is missing. Whereas the trace of fault 9 contains chlorite-epidote mineralization, such mineralization is absent within all of the subsidiary faults that intersect with fault 9. One subsidiary fault contained chlorite-epidote mineralization within its trace south of the intersection with the trace of fault 9, but not north of the intersection. Four of the subsidiary fault traces lacked any outcrop-scale evidence for mineralization. Thus the existence of slip on the traces of these subsidiary faults does not guarantee the presence of chlorite-epidote mineralization.

**Terminations, Junctions, Steps, and Stepovers.** As with the BCFZ, no single fracture or fault trace extends the entire length of the LCFZ. The three fracture traces terminate by either disappearing beneath a covered area or at a junction with individual fault traces at both ends (Table 4). Chlorite-epidote mineralization within the fracture traces continues along the entire trace of the fracture if that fracture disappears into a covered area. In addition, such mineralization also extends into the intersecting fault trace at those locations where the fracture terminates at a junction.

In contrast to fractures, the traces of the faults comprising the LCFZ may terminate in a variety of styles (Table 4). No individual fault trace terminates by the same style at both endpoints. Seven faults terminate by disappearing beneath a covered area at one end of their trace. Four faults have traces that terminate at a junction with a step connecting one fault trace to another. Two fault traces terminate as a simple junction with another trace. Two faults terminate as a horsetail splay structure. Three fault traces end by dying out at a tip and another two traces have endpoints that form a stepover between them. Finally, two fault traces, faults 9 and 11, terminate at the intersection of a subsidiary fault originating from the simple fault
TABLE 4. TERMINATION STYLES OF FRACTURE AND FAULT TRACES WITHIN THE LCFZ

<table>
<thead>
<tr>
<th>Type of trace</th>
<th>Termination style</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractures</td>
<td>Junction</td>
<td>50</td>
</tr>
<tr>
<td>(8 endpoints)</td>
<td>Covered</td>
<td>50</td>
</tr>
<tr>
<td>Faults</td>
<td>Covered</td>
<td>32</td>
</tr>
<tr>
<td>(22 endpoints)</td>
<td>Junction</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Die at a tip</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Fault*</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Stepover</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Horsetail splay</td>
<td>9</td>
</tr>
</tbody>
</table>

* Subsidiary faults at eastern end of fault zone.

zone near the eastern end of the LCFZ. As with the traces comprising the BCFZ, outcrop-scale evidence for slip does not indicate a particular style of termination. Likewise, the width of a fault trace does not appear to increase or decrease as the trace approaches the endpoint with the exception of those traces that terminate by dying out at a tip or as a horsetail splay structure. In these cases, the width of the fault trace decreases as the tip or the horsetail splay structure is approached.

No consistent pattern of mineralization within fault traces at their endpoints exists. If chlorite-epidote mineralization exists within the trace of a fault, then the mineralization will extend to the endpoints if the fault trace terminates at a junction, step, or stepover. In such cases, the mineralization will continue into the intersecting trace (Fig. 39). Those fault traces that terminate by dying out at a tip or by forming a horsetail splay structure may or may not have chlorite-epidote mineralization at their endpoints, even if such mineralization is present within other portions of the fault. At two locations where a fault trace terminates by dying at a tip (points K33 and M20), no chlorite-epidote mineralization is present at the tip. In contrast, chlorite-epidote mineralization is present at point M2, the southwestern endpoint of the trace of fault
11. Although chlorite-epidote mineralization is absent from the horsetail splay fractures at the end of the trace of fault 4, such mineralization is present within the splay fractures at the end of the trace of fault 8. Quartz mineralization is absent from all of the endpoints.

The two horsetail splay structures are not similar. Splays originating from the trace of fault 4 are curved and extend for ~10 cm away from the fault trace. In contrast, the splay fractures at the end of the trace of fault 8 extend away from the covered area as straight traces for ~20 to 30 cm before curving for a distance of ~25 cm.

The trace of fault 2 connects with the trace of fault 3 by way of a stepover. The traces connecting the two faults together strike from the fault traces at angles between 15° and 30° (Fig. 40). A secondary fracture connecting the two fault traces to one another exists within the stepover and strikes from the trace of fault 3 at an
angle of 36°. The trace of fault 3 actually extends past the stepover for 5 cm and ends at a tip. Another secondary fracture, striking in a northwest-to-southeast direction, crosses the stepover at an angle of 7° to the trace of fault 2 (Fig. 40). Episodic chlorite-epidote mineralization is widespread within the traces comprising the stepover whereas quartz mineralization is absent. The northwest-to-southeast striking secondary fracture lacks mineralization. The stepover is surrounded by a zone of altered granodiorite.

Most junctions within the LCFZ are simple structures, with a single trace branching off from another trace without secondary fracturing. If a fracture or fault trace contains chlorite-epidote mineralization, then such mineralization continues within the branching fracture or fault trace. Quartz mineralization at any of the junctions within the LCFZ is absent. Branching fracture or fault traces strike away from the original trace at angles ranging between 10° and 40°.

The junction at point L9 has secondary fractures within the acute angle between two separating traces typical of a complex junction structure (Fig. 41). The secondary fractures strike in a northeast-to-southwest direction and have angles
between 10° and 80° to the trace of fault 7. Chlorite-epidote mineralization is common within the secondary fractures, but is not present in every fracture. A single fracture extends from the step trace and continues subparallel to the trace of fault 7 between the acute angle separating the fault trace with the step trace (Fig. 41). This fracture trace lacks chlorite-epidote mineralization.

Only two steps are exposed along the trace of the LCFZ (fractures 2 and 3). Both step to the left and are mineralized to a chlorite-epidote assemblage. Alteration of the surrounding granodiorite is present along the entire length of each step. The length of the step traces range from 1 to 1.5 m. The angle between the step and the connecting fault traces range between 15° and 45°.

**Fault Step Complex.** The trace of fault 6 connects with the trace of fault 7 by way of a fault step complex (Fig. 42). This fault step complex is smaller than the one within the BCFZ, being only 3.2 m long and 1 m wide. Ten splay fractures connect the two fault traces together and there are four secondary fractures within the fault step complex. All of the fracture and fault traces comprising the fault step complex are surrounded by a zone of altered granodiorite. Quartz mineralization within any of these traces is absent.

From the west, the trace of fault 6 enters the fault step complex at a junction

*Figure 41. Drawing of a complex junction between points L9 and L10. See Plate 3 for location.*
Figure 42. Drawing of the fault step complex within the LCFZ. Splay fractures extend across the fault step complex, whereas the secondary fractures only extend from fault 6 to a splay fracture. See Plate 3 for location.
with the westernmost splay fracture (Fig. 42). The trace of fault 6 continues northeastward with an attitude of 50°, 75°SE taken at point K32. This fault trace terminates at point K33 by dying out at a tip (Fig. 42). Chlorite-epidote mineralization is present within the trace of fault 6 up to the junction with the easternmost splay fracture. Between this junction and point K33, mineralization within the fault trace is absent.

The trace of fault 7 enters the fault step complex at point K31 and continues southwestward to point K30 with an attitude of 71°, 84°SE (Fig. 42). At point K30, the trace of this fault terminates at a junction with the westernmost splay fracture. The trace of fault 7 contains chlorite-epidote mineralization along its entire length within the fault step complex.

The splay fractures branch away from the fault traces at angles ranging between 64° and 90° (Fig. 42). Attitudes of these splay fracture traces are estimates, as the quality of exposure is poor. These attitudes range between 150°, 74°SW and 188°, 62°NW (Fig. 34b). Each splay fracture is mineralized to a chlorite-epidote assemblage except for the westernmost splay fracture, which contains chlorite-epidote mineralization in only the northernmost 60 cm of its ~1 m length.

Branching from the trace of fault 6 and intersecting with two splay fractures are three secondary fractures ranging in length from 7 to 46 cm long (Fig. 42). These secondary fractures form angles of 63°, 35°, and 88° with the trace of fault 6 from west to east. None of these secondary fractures contain chlorite-epidote mineralization. An attitude of 346°, 84°NE was taken from one secondary fracture, whereas a second fracture has an attitude of 321°, 72°NE (Fig. 34b).

Bisecting the width of the fault step complex is a secondary fracture which crosses all ten splay fractures (Fig. 42). This secondary fracture is straight and linear, but is not parallel to either of the two fault traces. Furthermore, as the secondary
fracture continues northeastward, it bends to the southeast and continues until
dying out at a tip just past the intersection with the easternmost splay fracture. None
of the splay fractures have offset this secondary fracture, nor has the secondary
fracture offset any of the splay fractures. Chlorite-epidote mineralization is absent
from the trace of this secondary fracture. Whether this secondary fracture developed
before, during, or after the development of the fault step complex is not known.
Interestingly, the fault step complex within the BCFZ also contains a trace, fault 26,
that cuts across the width of the fault step complex. Such bisecting traces may be
characteristic of fault step complexes.

Dikes and Slip Distribution. There are 10 aplite dike traces cut by the
LCFZ (Plate 3). Four of these dike traces cross the width of the fault zone, whereas
the remaining six partially extend across the LCFZ. All the dike traces strike
northwest-southeast. However, dip directions may be to the northeast or the
southwest (Fig. 34c). None of the dike traces extend across the fault step complex or
are located alongside the subsidiary faults at the eastern end of the LCFZ. Whereas
most of the intersections between dike and fault traces are sharp, several intersections
have appearances suggesting complex dike-fault interaction, such as ductile flow of
the aplitic material along the fault trace and extensive chlorite-epidote mineralization
within the fault trace. In this portion of the LCFZ section, the location, geometry,
physical characteristics, and offsets of the dike traces within the LCFZ are described.
In addition, a discussion of the slip distribution within the LCFZ is presented.

The trace of dike 1 is located within the westernmost outcrop of the host
granodiorite (Plate 3). This dike trace is first exposed at point K7 along the trace of
fault 4. South of this fault trace, the trace of dike 1 is beneath a covered area. Only
the western edge of this dike trace is exposed north of the fault at point K7, as the
remaining portion of the dike is missing from the outcrop. Between points K7 and
K3, the full width of the dike trace becomes exposed on the outcrop. At point K3, the trace of fault 2 offsets the dike trace 27 cm. Northwest of the intersection with the trace of fault 2, the trace of dike 1 crosses the trace of fracture 1 and extends beyond the LCFZ. This dike trace has a constant width of ~20 cm.

The trace of dike 2 enters the LCFZ from the southeast with a width of 45 cm (Plate 3). At point K15, this dike trace intersects the trace of fault 5 with an offset of 6 cm (Table 5). The trace of dike 2 continues northwestward, decreasing in width from 45 to 28 cm, to point K8 on the trace of fault 4. This dike trace is offset 24 cm by the trace of fault 4. From the intersection with the trace of fault 4, the dike trace continues, with a width of 28 cm, into a covered area (Plate 3). The dike trace does not reappear from beneath this covered area.

The traces of dikes 3, 4, and 5 are located in an area where only a small amount of the host granodiorite is exposed (Plate 3). The trace of dike 3 intersects the trace of fault 4 at point K10 (Fig. 35). A small portion of the dike trace is exposed south of this fault trace before disappearing beneath a covered area. North of the fault trace, the trace of dike 3 curves to the north, intersecting the traces of dikes 4 and 5, and continues beneath a covered area. An exact offset of this dike trace by the trace of fault 4 is not possible because the aplitic material of the dike appears to be smeared, or ductilely deformed. However, an estimated offset of 13 cm was obtained.

The southeastward projection of the trace of dike 3 beyond the covered area is somewhat problematic. The southern edge of this covered area is the trace of fracture 2 (Plate 3). South of this fracture trace, the host granodiorite is completely exposed, but no evidence for the continuation the the trace of dike 3 exists. It appears unlikely that the dike trace simply terminated beneath the covered area whereas the adjacent traces of dikes 4 and 5 continue southeastward. But field
TABLE 5. OFFSET OF DIKE TRACES THAT EXTEND ACROSS THE WIDTH OF THE LCFZ

<table>
<thead>
<tr>
<th>Dike</th>
<th>Fault</th>
<th>Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dike 4</td>
<td>Fault 4</td>
<td>20*</td>
</tr>
<tr>
<td></td>
<td>Fault 6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Total across LCFZ</td>
<td>26</td>
</tr>
<tr>
<td>Dike 5</td>
<td>Fault 4</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Fault 6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Total across LCFZ</td>
<td>36</td>
</tr>
<tr>
<td>Dike 6</td>
<td>Fault 1</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Fault 3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Fault 6</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Total across LCFZ</td>
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</tr>
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<td>Fault 8</td>
<td>23</td>
</tr>
<tr>
<td>Dike 9</td>
<td>Fault 9</td>
<td>18</td>
</tr>
<tr>
<td>Dike 10</td>
<td>Fault 10</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fault 9</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Fault 11</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Total across LCFZ</td>
<td>30</td>
</tr>
</tbody>
</table>

* Estimated value.

evidence suggesting a more reasonable explanation is absent.

The trace of dike 4 enters the LCFZ from the southeast and is offset by the trace of fault 6 at point K13 (Plate 3). The dike trace is offset 6 cm at this location (Table 5). Continuing northwest from the trace of fault 6, the dike trace disappears beneath a covered area and does not reappear until north of the trace of fault 4 (Fig. 35). Projecting the dike trace across the covered area to an intersection with the south side of fault 4 gives an estimated offset of 20 cm. The trace of dike 4 eventually intersects the trace of dike 3 and disappears beneath a covered area.

As with the trace of dike 4, the trace of dike 5 enters the fault zone from the southeast (Plate 3). Unlike the traces of dikes 3 or 4, the trace of dike 5 is completely exposed until the intersection with the trace of dike 3 and the eventual disappearance beneath a covered area. Along the trace of fault 6, this dike trace is
offset 10 cm (Table 5). Northwestward, this dike trace crosses the trace of fracture 3 without being offset, and intersects the trace of fault 4. Along this fault trace, the trace of dike 5 is offset 26 cm (Fig. 35). The trace of dike 5 has a constant width of 20 cm. As with the trace of dike 3, the trace of dike 5 appears to have been ductilely deformed while being offset along the trace of fault 4.

The trace of dike 6 is the first to extend across the entire width of the LCFZ. This dike trace emerges from beneath a covered area and extends in a northwestern direction until intersecting the trace of fault 6 between points K27 and K28 (Plate 3). This dike trace is offset 40 cm along the trace of fault 6, the largest offset within the LCFZ (Table 5). In addition, the contact between the dike and fault traces is not sharp, suggesting that ductile deformation along the fault trace may have occurred.

Only the traces of faults 4 and 6 have intersecting dike traces that are ductilely deformed. Furthermore, ductile deformation is absent at all fault and dike intersections within the BCFZ. Bürgmann and Pollard (1994) proposed that during the fault-growth process, some areas along a fault may undergo localized increases in temperature, thereby producing ductile deformation in the surrounding rock. Propagation of faults 4 and 6 may have resulted in localized temperature increases in the host rock. However, this hypothesis does not explain why ductile deformation fabrics are present in only the aplite dikes and not the surrounding host rock.

Christiansen and Pollard (1997) have inferred from studying aplite dikes within the nearby Mono Creek Granite that the fine-grain size and equant character of feldspar, and the lack of interlocking textures, make the aplite dikes significantly weaker than the surrounding rock, causing shear strain to be localized along dikes. This hypothesis, combined with localized temperature increases, may explain why some dike traces are ductilely deformed at their intersections with faults.

Continuing from point K27, the trace of dike 6 extends across the outcrop
until intersecting the trace of fault 2 at point K22 (Plate 3). The dike trace is offset 20 cm by this fault trace. Along the trace of fault 1, the trace of dike 6 is offset 19 cm. From point K19, the trace of dike 6 continues out of the LCFZ with an attitude of 281°, 45°NE. The dike trace has a constant width of 19 cm.

After emerging from beneath a covered area, the trace of dike 7 extends in a northwest direction with an attitude of 70°, 83°SW until intersecting the trace of fault 2 at point L7 (Plate 3). This dike trace is offset 12 cm by the trace of fault 2. From point L7, the trace of dike 7 continues out of the LCFZ with an attitude of 93°, 70°S. Why this dike trace has two dissimilar attitudes is unknown. The overall strike of the dike trace does change at the intersection with the trace of fault 2, but not enough to justify a 23° difference. Possibly some rotation about a vertical axis occurred at point L7, or that one or both of the attitudes are inaccurate.

The trace of dike 8 emerges from beneath a covered area and intersects the trace of fault 8 between points L13 and L14 (Plate 3). The offset of this dike trace by the trace of fault 8 is 23 cm. From point L13, the dike trace extends in a northwest direction, crossing the trace of fracture 4 at point L15, and continues out of the LCFZ.

At point L21, the trace of fault 9 offsets the trace of dike 9 by 18 cm. North of the fault trace, this dike has an attitude of 330°, 30°NE. The dike trace has a constant width of 14 cm.

The easternmost dike trace within the LCFZ is dike 10 (Plate 3). This dike trace originates from the simple fault zone and is offset by the traces of faults 9, 10, and 11 by 19 cm, 9 cm, and 2 cm, respectively (Table 5). The larger amount of offset along the trace of fault 9 is attributed to the fact that this fault trace is longer and has a larger amount of slip distributed along its length than the other two fault traces. Northwestward from point M16 on the trace of fault 10, the trace of dike 10
continues out of the LCFZ with a strike of 317°. No dip measurement was obtainable.

The location and amount of offset of dike traces by the faults comprising the LCFZ raises interesting observations about the distribution of slip within the fault zone. For this discussion, it will be assumed that a fault grows in the direction of decreasing slip, from the region of highest accumulated slip to the lowest (Cowie and Scholz, 1992a). This assumption can be used to illustrate the numerous slip distribution patterns possible within the LCFZ. The validity and implications of using this assumption are presented in the Discussion section.

The distribution and amount of dike offset on the traces of faults 2 and 3 suggest that either these two faults grew towards each other, or that slip was transferred from fault 2 to fault 3. The amount of offset on the trace of fault 2 decreases northeastward from 27 to 20 cm, indicating that the fault grew towards the stepover. The trace of fault 3 has only one offset, making it impossible to determine the growth direction. A southwestward growth direction for fault 3 would suggest that the traces of faults 2 and 3 grew towards each other until connecting together via the stepover structure. However, if the trace of fault 3 grew northeastward, then the combined traces of both faults would have an overall northeastward decrease in offset from 27 to 12 cm. If the latter scenario is correct, then the stepover structure between faults 2 and 3 developed as a means to transfer slip from the trace of fault 2 to the trace of fault 3.

Complicating the above discussion is whether the trace of fault 1 connects with the trace of fault 3 between points K20 and L5. The trace of fault 1 has a northeastward decrease in offset from 19 to 12 cm. Thus connection with the trace of fault 3 between points K20 and L5 would suggest a northeastward growth direction for the combined traces of faults 1 and 3. Overall, the trace of fault 3 would appear
to act as the northeastward continuation of both faults 1 and 2.

The slip distribution along those fault traces which come together as the fault step complex also provide several possible fault-growth scenarios. The trace of fault 6 shows a decrease in dike trace offsets away from the fault step complex. The direction of growth for fault 7 cannot be constrained because this fault trace does not offset any dikes. Assuming that the trace of fault 7 also grew away from the fault step complex, then the two faults (6 and 7) nucleated at or near the fault step complex (Fig. 43a). If nucleation began near the fault step complex, the complex acts as a transfer structure between the two fault traces. But none of the splay or secondary fractures within the fault step complex have offsets along their traces. A second scenario is that slip along the traces of faults 6 and 7 is independent of one another and that the fault step complex represents the nucleation of a simple fault zone (Fig. 43b). Such a scenario would be independent of whether the fault traces are growing away from, or towards, the fault step complex. The overall geometry of the fault step complex and the simplicity of the second scenario suggests that the latter scenario is the more plausible sequence of events.

Unlike the above discussion, slip distribution on the trace of fault 4 is unambiguous. The offset of dike traces by this fault indicates first an increase, then a decrease in slip towards point K10 from both ends of the trace (Fig. 44). Thus according to Cowie and Scholz (1992a), the trace of fault 4 is actually a combination of two separate fault traces that coalesced near point K10. However, no evidence indicating the combining of two fault traces at, or near, this location is present (Fig. 35).

Graphs of the dike offset distribution and the cumulative displacement-length profile of the LCFZ are shown in Figure 45. Like the BCFZ, the dike offsets are irregularly distributed along the trace of the fault zone (Fig. 45a). The offsets across
Figure 43. Possible scenarios for the growth of faults 6 and 7 within the LCFZ. (a) Nucleation of the fault step complex as faults 6 and 7 propagate away from each other. (b) Nucleation of the fault step complex as a result of faults 6 and 7 propagating towards each other.
Figure 44. Displacement-length profile for the trace of fault 4 within the LCFZ. The profile has an irregular curve with a substantial dip near point K10. See text for discussion. Error bar indicates that the exact southwestern endpoint of fault 4 is unknown.

Individual faults range from 9 to 40 cm, with an average offset of 17.3 cm. The cumulative displacement-length profile has an irregular shape (Fig. 45b), similar to the displacement-length profiles of the BCFZ (Fig. 32b) and the trace of fault 4 (Fig. 44). The displacement-length profile also has steep displacement gradients (~1/4 and ~1/8) from both endpoints. The peak in the profile coincides with the area around point K10 (Plate 3). A possible explanation for the dip in the profile between 65 and 90 m is that the fault zone consists of only one fault trace in this area, thereby limiting the cumulative slip to the actual dike offsets along this fault trace.

Jim's Ridge Fault Zone

Jim's Ridge Fault Zone (JRFZ) is the smallest fault zone discussed in this study. Like the LCFZ, the JRFZ does not contain simple fault zones nor do the fracture and fault traces form fracture networks. Unlike the LCFZ, there is no fault step complex within the JRFZ. The JRFZ is 1.2 km northwest of the LCFZ and transverses over a 2900 m high ridge west of Bear Creek (Fig. 1). This fault zone
Figure 45. Displacement-length profile for the LCFZ. (a) Distribution of dike offsets across individual faults along the trace of the fault zone. (b) Displacement-length profile based on the cumulative offsets of those dike traces that cross the fault zone. The resulting profile has an irregular shape and steep displacement gradients at both endpoints. See text for discussion. Error bar indicates that the exact southwestern endpoint of the fault zone is unknown.
extends in a N60°E direction and is ~60 m long. Plate 4 is a the map view of the LCFZ showing the overall geometry of the fault zone.

The western end of the JRFZ is located on the west side of the ridge at point P28 (Plate 4). From this point, the JRFZ extends northeastward over a gently increasing slope towards the top of the ridge (Fig. 46a). The ridge-top is flat and extends for a short distance (Fig. 46b). At the eastern crest of the ridge, the fault zone continues down the eastern face of the ridge to point P1, which marks the eastern end of the JRFZ (Fig. 46c). The endpoints of the JRFZ are artificial, as the fault traces comprising the fault zone continue beyond these endpoints. The location of a stepover structure exposed in three dimensions and sufficient vertical relief to construct a three-dimensional representation of the fault zone trace were the main criteria used to establish the boundaries of the JRFZ. In addition, the location of aplite dikes also constrained the location of the endpoints.

The control point for the JRFZ is labelled CP and is located 15.5 m northeast of the western end of the fault zone (Plate 4). The lowest elevation within the JRFZ is at point P28, which has an elevation of -3.32 m relative to the control point. The vertical relief between point P28 and the highest point, point P6, is 9.34 m. Northeast of point P6, the vertical relief decreases by 1.47 m at point P1.

The JRFZ is composed fault traces that combine to form a long primary fault trace and a single fault trace that forms a shorter secondary fault trace. The primary and secondary fault traces intersect at a crossover at point P12 (Plate 4). Obliquely-striking transfer fracture and fault traces, as well as steps, are not present within the JRFZ. A stepover structure exposed in three dimensions is located between points P19 and P23 (Plate 4). Slickenlines with rakes to the east are exposed along vertical fault surfaces at points P1, P10, and 1.5 m southwest of point P25. Outcrop-scale evidence verifying the presence of joints within the JRFZ is absent. No rock samples
Figure 46. Jim's Ridge Fault Zone. (a) View eastward from west of point P23. Stepover is in the foreground. The host granodiorite is relatively smooth and unfractured. (b) View eastward from point P9. The fault zone is flat in this area. (c) View eastward from point P6.
were taken from this fault zone.

Five aplite dike traces are cut by the JRFZ. Four of these dike traces intersect the primary fault trace and the other intersects the secondary fault trace. All of the dike traces are left-laterally offset. One left-laterally offset mafic inclusion is located between points P16 and P17.

The following discussion of the JRFZ is organized differently than the two previous fault zone descriptions. The portion describing the geometry of the fracture and fault traces also includes a description of the dike traces. In addition, a discussion of the slip distribution along the trace of the JRFZ is included in the geometry section. A description of the physical features and mineralization within the individual fracture and fault traces, as well as the various termination styles and the physical characteristics of the junctions and the crossover, follows. Finally, a description of the stepover structure is given.

**Fault Zone Geometry.** The trace of the JRFZ is made up of three fault traces (faults 1, 2, and 3) that combine to form a primary fault trace which extends the length of the fault zone (Plate 4). A single fault trace (fault 4) comprises the shorter secondary fault trace. One fracture trace (fracture 1), as well as several splay fractures, are located at the western end of the secondary fault trace. The faults within the JRFZ have attitudes consistent with the other two fault zones investigated in this study (Fig. 47a). The dike traces are numbered from 1 to 5 (Plate 4), and have consistent northwest-to-southeast strikes with northeast-to-southwest dip directions (Fig. 47b). Slickenlines exposed within the JRFZ have rakes that cluster closely in the northeastern quadrant on a stereogram (Fig. 47c). This plot is similar to the one from the BCFZ (Fig. 12f), indicating that the last motion on the faults in the JRFZ was strike-slip.

The trace of fault 1 begins at point P28, the western end of the JRFZ, and
Figure 47. Equal-area stereograms of the faults, dikes, and slickenlines within the JRFZ. All stereograms are lower-hemisphere projections. (a) Poles of fault traces. As with the BCFZ (Fig. 12a) and the LCFZ (Fig. 34a), the general orientation of the fault traces is northeast-to-southwest, with dips to the southeast. (b) Poles of dike traces. (c) Rakes of slickenlines. The rakes plot in the same quadrant as those in the BCFZ (Fig. 12f).
extends to point P19 within the stepover structure (Plate 4). The trace of fault 1 continues southwestward from point P28 down the ridge into a small canyon. Northeast of point P28, this fault trace offsets the trace of dike 1 by 5 cm at point P27. The attitude of the fault trace at this point is 53°, 74°SE whereas the dike trace has an attitude of 328°, 35°NE. At point P26, the attitude along the trace of fault 1 is 53°, 80°SE, indicating a steeping of the fault surface. Approximately 1.3 m northeast of point P26, an attitude of 54°, 81°SE was taken on the trace of fault 1. In addition, slickenlines exposed at this location have a rake of 9°E. At point P24, the attitude along the trace of fault 1 is 62°, 75°SE. Point P23 marks the southwestern end of the stepover connecting the traces of faults 1 and 2 to each other.

The trace of fault 2 extends northeastward from within the stepover to point P8 (Plate 4). Point P12 locates the crossover with the trace of fault 4. An attitude of 58°, 80°SE was taken from the trace of fault 2 at point P11. At point P10, this fault trace has an attitude of 56°, 81°SE as well as slickenlines having a rake 10°E. Approximately 4.8 m northeast of point P11, the trace of dike 2 abuts against the trace of fault 2 from the southeast. There is no continuation of this dike trace north of the fault trace (Plate 4). The host granodiorite north of the trace of fault 2 at this location drops in elevation by ~1.5 m, exposing the vertical plane of the fault surface. The trace of dike 2 is not present in the vertical plane, suggesting that the dike does not extend through the fault surface.

Between points P10 and P9, the trace of fault 2 increases in elevation as it reaches the ridge crest. An attitude of 60°, 80°SE was taken at point P9. At point P8, the trace of fault 2 ends at a junction with the trace of fault 3 (Plate 4).

Northwest of point P9, the trace of fault 3 begins. There is a drop in elevation by ~1.5 m of the host granodiorite southwest of this endpoint. While the fault trace is present in the exposed vertical plane of the host granodiorite, there is no
continuation of this fault trace southwestward. An attitude of 57°, 79°SE was taken from the trace of fault 3 at this endpoint.

Northeastward, the trace of fault 3 extends across the ridge-top towards point P1 and the eastern end of the JRFZ. Between points P8 and P6, the trace of fault 3 disappears and reappears from beneath two covered areas (Plate 4). An attitude of 59°, 79°SE was taken from the fault trace at point P6. At point P5, this fault trace offsets the trace of dike 3 by 25 cm. This dike trace has an attitude of 299°, 74°NE at this point. The trace of dike 4 intersects the trace of fault 3 at point P4 and is offset 38 cm (Plate 4). A strike of 312° was taken from the trace of dike 4, but no dip measurement was obtainable.

Points P3 and P2 mark the offset of the dike 5 trace by the trace of fault 3 (Plate 4). This dike trace has an attitude of 155°, 23°SW and is offset by the fault trace 41 cm. From point P2, the trace of fault 3 continues northeastward until reaching the eastern end of the JRFZ at point P1. An attitude of 63°, 86°SE was taken from the fault trace at point P1. Slickenlines exposed along the fault trace at point P1 have a rake 8°E. Northeastward of point P1, the fault trace continues down the ridge and out of the fault zone.

The trace of fault 4 comprises the secondary fault trace. This fault trace emerges from beneath a covered area at point P17 (Plate 4). The trace of fault 4 offsets a mafic inclusion northeast of point P17 by 22 cm. The junction with the trace of fracture 1 occurs at point P16. An attitude of 75°, 77°SE was taken from the fault trace at point P15. Northeastward from the crossover with the trace of fault 2, the trace of fault 4 offsets the trace of dike 2 by 30 cm at point P13 (Plate 4). This dike trace has an attitude of 329°, 85°NE. Point P14 marks the eastern end of the trace of fault 4. While the fault trace continues beyond this point, the width of the trace decreases until it is no longer visible.
The trace of fracture 1 extends southwestward from the junction with the trace of fault 4 at point P16 to a covered area (Plate 4). There is no continuation of this fracture trace west of the covered area.

The amount of slip within the JRFZ appears to decreases southwestward (Fig. 48). Along the trace of the primary fault, the offsets decrease from 41 cm at point P2 to 5 cm at point P27. However, this observation assumes that slip was transferred between the traces of faults 1, 2, and 3. The trace of fault 3 unequivocally shows a

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Figure 48. Displacement-length profile for the JRFZ. The profile has an irregular curve, but indicates a southwestern decrease in slip along the fault zone. This displacement-length profile differs from the ones for the BCFZ (Fig. 32b) and LCFZ (Fig. 45b) because the fault traces comprising the JRFZ continue beyond the fault zone into the host granodiorite.
southwestward decrease in slip because the three dike traces offset by this fault trace have offsets that decrease in this direction. A convincing argument for slip along the trace of fault 2 requires locating the continuation of dike 2 north of the trace of fault 2. But the presence of outcrop-scale deformation within the host granodiorite at the crossover, as well as the presence of the stepover, suggests that slip may have occurred along the trace of fault 2. Whether such slip was transferred from the trace of fault 3 is uncertain. Although slip within the JRFZ appears to decrease southwestward, the faults comprising this fault zone continue beyond the JRFZ. Thus the slip distribution shown in Figure 48 only represents a portion of the overall slip that might have occurred on the fault traces.

The displacement-length profile for fault 4 indicates a southwestward decrease in slip (Fig. 49). The displacement gradient is steep (~1/8) away from the endpoint of the fault trace, similar to the displacement-length profiles of individual faults within the BCFZ (Fig. 31). Northeastward away from the first offset, the slope of the displacement-length profile decreases, like the profile for fault 15 within the

Figure 49. Displacement-length profile for fault 4 within the JRFZ. The fault terminates beneath a covered area on the southwestern end and continues beyond the fault zone on the northern end. As with the faults within the BCFZ (Fig. 31), the profile has a steep displacement gradient near the endpoint of the fault trace. The profile then increases gradually along the trace of the fault.
BCFZ. Thus a steep displacement gradient from a fault’s endpoint, followed by a decrease in the gradient, may be characteristic of individual fault traces. The implications of this feature are presented in the Discussion section.

**Individual Fractures and Faults.** All of the fractures and faults within the JRFZ have straight linear traces. The fault traces have lengths ranging from 19 to 30 m. The widths of the traces within the fault zone are small, between 1 and 10 mm, with the average width being ~4 mm. Unlike the other two fault zones, the widths of the fault traces comprising the JRFZ are consistent along the length of the trace, only varying by ±3 mm. The trace of fracture 1 maintains a constant 3 mm width along its entire length. As with the other two fault zones, the traces within the JRFZ have sharp margins between the trace material and the adjoining host granodiorite.

In contrast to the BCFZ and LCFZ, mineralization within the fracture and fault traces comprising the JRFZ varies less in terms of width, composition, and location. Chlorite-epidote mineralization is present within the entire length of all the fracture and fault traces. Pockets of quartz mineralization are present along the trace of fault 4 and at the junction between this fault trace and the trace of fracture 1. Quartz mineralization is not restricted to fault traces, but is also present intertwined with the chlorite-epidote assemblage within the trace of fracture 1. Episodic chlorite-epidote mineralization is absent within all of the fracture or fault traces comprising the JRFZ. Episodic mineralization may have occurred, but the small trace widths makes finding outcrop-scale evidence for episodic mineralization difficult.

Alteration of the granodiorite surrounding the fracture and fault traces located within the BCFZ and LCFZ is also present within the JRFZ. These altered zones are not randomly distributed along the fracture or fault traces, but surround the entire length of each trace within the JRFZ. The altered granodiorite extends outwards ~1 cm away from both sides of the trace. However, alteration of the granodiorite is
absent on either side of a fault trace where the trace is exposed in the vertical plane. As within the LCFZ, the altered granodiorite does not have a raised rib-like appearance, but is the same height as the surrounding unaltered host granodiorite. Exceptions to the above observations are discussed below in the stepover portion of this section.

Where a fault trace is exposed in the vertical plane, only the trace of the fault is present. No subsidiary fractures, similar to those found within the vertical exposures located in the BCFZ, are present. The width of the vertical fault trace does not vary with depth. Only chlorite-epidote mineralization is present within vertical fault traces. In contrast, where a fault surface is exposed in the vertical plane, quartz mineralization is present among the chlorite-epidote assemblage.

As with the BCFZ and LCFZ, none of the fracture or fault traces comprising the JRFZ extend the entire length of the fault zone. The trace of fracture 1 terminates by intersecting the trace of fault 4 at a junction on one end and by disappearing beneath a covered area on the other end. The fault traces terminate by joining together or by continuing beyond the fault zone. The traces of faults 1, 3, and 4 all have one endpoint in which the fault trace extends out of the fault zone. Only the trace of fault 2 is contained entirely within the JRFZ. The southwestern endpoint of this fault trace forms a stepover with the trace of fault 1, whereas the northeastern endpoint is a junction with the trace of fault 3. The trace of fault 3 terminates on the southwest by dying out at a tip. The southwest end of fault 4 disappears beneath a covered area. No horsetail splay fractures are present within the JRFZ.

As the trace of fault 3 approaches its southwestern endpoint, the width of the fault trace decreases as the endpoint is approached. The trace of fault 3 maintains this small width in the vertical plane. A chlorite-epidote assemblage is present within the fault trace, both at the tip and within the vertical exposure. As mentioned above,
the trace of this fault does not continue into the host granodiorite west of the endpoint. Assuming that the width of a fault surface decreases towards the edge of that fault surface, then the decreasing width of this fault trace, along with the fact that the trace does not continue westward beyond the tip, suggests that the trace exposed in the vertical plane is the actual edge of the fault surface.

Two junctions are present within the JRFZ (points P8 and P16). Each of these junctions is a simple structure, lacking secondary fractures within the acute angle between the separating traces or subsidiary fractures within the surrounding granodiorite. The acute angle between the separating traces at the junction between the traces of fracture 1 and fault 4 is 24°, whereas the acute angle is 6° at the junction between the traces of faults 2 and 3. The width of the traces does not change as the junction is approached. At the junction between the traces of faults 2 and 3 (point P8), only chlorite-epidote mineralization is present, whereas both chlorite-epidote and quartz mineralization is present at the junction between the traces of fracture 1 and fault 4 (point P16). At this junction, the quartz mineralization is present within the acute angle formed by the separating traces. A rim of chlorite-epidote mineralization separates the quartz mineralization from the host granodiorite.

Splay fractures branch off from the traces of fracture 1 and fault 4 near the junction. The splay fractures branching away from the fault trace are 7.5 to 12 cm long and strike away at angles between 33° and 40°. In contrast, those splay fractures branching away from the fracture trace are 0.5 to 4.5 cm long and strike away at angles between 27° and 40°. Chlorite-epidote mineralization may or may not be present within the splay fractures. If present, such mineralization does not always extend the length of the splay fracture. Quartz mineralization is absent from any of the splay fractures.

The crossover between the traces of faults 2 and 4 (point P12) does not have
the complex structure similar to those crossovers found within the BCFZ. The two intersecting fault traces form an acute angle of 18° between their traces. The width of both traces increases at the crossover. Only chlorite-epidote mineralization is present within the traces at the crossover in outcrop-scale. The surrounding granodiorite sits higher than the surrounding rock by ~4 mm, but this granodiorite is not altered. Splay fractures within the acute angle between the intersecting traces, as well as subsidiary fractures in the obtuse angles, are absent. Instead, the host granodiorite between the acute and obtuse angles has a schistose fabric indicative of ductile shear.

The Stepover. The traces of faults 1 and 2 connect together by forming a stepover structure (Plate 4). Unlike the stepovers within the BCFZ and LCFZ, this stepover is exposed in three dimensions, allowing for the investigation of both the horizontal and vertical characteristics of such a structure. The geometry and physical features of the fracture and fault traces that form this stepover, as well as the characteristics of the rock volume bounded within the structure, are described in this section.

The stepover is located on a small limb of the host granodiorite which extends 76 cm above the surrounding rock on the east and 40 cm on the west. From the southwest, the trace of fault 1 enters the stepover below point P23 and extends upwards over the western side of the limb (Fig. 50a). Once over the top of the limb, the fault trace extends downwards until intersecting the surrounding granodiorite (Fig. 50b) and continues northeastward along the flat portion of the host granodiorite. This fault trace steps to the left and connects with the trace of fault 2 at point P19 (Plate 4).

The trace of fault 2 enters the structure from the northeast and transverses over the limb northwest of, and parallel to, the trace of fault 1 (Plate 4). Between
Figure 50. Stepover structure within the JRFZ. (a) View to the east. A curved trace branching from below point P23 joins the trace of fault 1 to fault 2. The rock between the fault traces is altered, whereas the rock away from the stepover is not altered. (b) View to the west. The height of the eastern side of the limb is \( \sim 65 \) cm.
points P21 and P23, the trace of fault 2 extends down the limb 18 cm and then steps to the left by curving towards a junction with the trace of fault 1 at point P23 (Fig. 50a). The distance between the two parallel fault traces over the limb is 24 cm.

The stepover has an intact and unbroken appearance. Structurally, the stepover is composed of only the two fault traces and the connecting step fractures. No splay fractures are present within the rock volume bounded by the two fault traces. There are no fractures branching away from the fault traces into the surrounding host granodiorite. Secondary fracturing is absent within the bounded rock volume located on the flat portion of the stepover east of the limb.

Chlorite-epidote mineralization is present within both the fault traces and the two step fractures. Quartz mineralization is absent. Interestingly, the altered granodiorite commonly found surrounding both sides of the fracture and fault traces within all three fault zones is restricted to within the rock volume bounded by the two fault traces on the limb itself. No alteration of the granodiorite is present north of the fault 2 trace, or south of the fault 1 trace, as these two faults cross over the limb. In addition, the step trace which originates from point P23 and connects with the trace of fault 2 only has altered granodiorite above its trace (Fig. 50a). Where the two fault traces continue away from the eastern side of the limb, alteration zones are present on both sides of the fault traces, as well as the step fracture connecting fault 1 to fault 2 at point P19.

The fault traces do not increase or decrease in width as the traces transverse over the limb. The widths of the two step fracture traces also do not change relative to the connecting fault traces. The junctions at points P23 and P19 do not show any change in mineralization composition or trace width. Secondary fractures within the acute angles formed by those junctions are absent.

Attitudes were taken from both fault traces along the top of the limb. An
attitude of 60°, 83°SE was taken from the trace of fault 1 at point P22. Along the trace of fault 2, an attitude of 58°, 85°SE was taken between points P20 and P21 (Plate 4). Along the top of the limb, bounded by both fault traces, is a slip surface with exposed slickenlines (Fig. 51). This slip surface abuts the trace of fault 1 and is located ~20 cm from the eastern edge of the limb. The slip surface extends 9 cm away from the trace of fault 1 and convexes in an northeastward direction. The attitude of this surface is 346°, 34°NE. The exposed slickenlines have a rake of 34° and a direction of 60°. Chlorite-epidote mineralization is present along this slip surface, but the presence of quartz could not be established.

Summary of Field Observations

The three fault zones investigated for this study represent different levels of fault zone development and complexity. The Bear Camp Fault Zone is the largest and most developed of these fault zones, containing two simple fault zones, four fracture networks, a fault step complex, and up to 5.3 m of slip distributed along its

Figure 51. View of the slip surface within the stepover structure. The slip surface contains slickenlines. Top of photo is south.
trace. The Lower Camp Fault Zone contains several coalescing fracture and fault traces which extend the length of the fault zone, and a fault step complex. Jim's Ridge Fault Zone, the smallest of the three fault zones, is comprised of two intersecting fault traces. Below is a summary of the major observations from these three fault zones.

**Geometry.** The fault zones range from ~60 to 140 m in length and 1 to 12 m in width. All three fault zones extend in a southwest-to-northeast direction. The vertical relief along the fault zones range from ~10 to 33 m. The fault zones consist primarily of an array of parallel to subparallel fracture and fault traces that are separated from one another by intact rock. None of the fracture or fault traces extend the entire length of any of the three fault zones. At most, individual faults span 35% of a fault zone. The existence of joints, either within the host granodiorite preceding the nucleation of the fault zones, or forming as the fault zones developed, could not be verified at the microscopic or outcrop scale.

Simple fault zones are only present within the BCFZ. These simple fault zones are 25 to 31 m long, and vary in width along their trace from 1.5 to 2.5 m for the eastern simple fault zone and 1.0 to 1.8 m for the western simple fault zone. The boundary faults bordering the simple fault zones clearly define a separation between the unfractured granodiorite outside the simple fault zones and the fractured rock within the simple fault zones. The amount of brecciation and mineralization within the fractured rock volume changes along the trace of the simple fault zones. Furthermore, the physical appearance of the fractured rock volume within the western simple fault zone differs from that in the eastern simple fault zone.

Generally, the fracture and fault traces are straight and linear. Curved traces are restricted to transfer fractures or faults within the simple fault zones or within a fault step complex. The spacing between parallel to subparallel fracture and fault
traces range from 25 cm to 7 m, with the average spacing being between 1.3 and 1.5 m (Figs. 15 and 36). Fracture and fault trace lengths range from 2 to 56 m. Fracture and fault trace widths are not consistent along length and appear to be a function of the amount of fault zone development and complexity. Trace widths vary from 1 to 40 mm within the BCFZ, 1 to 15 mm within the LCFZ, and 1 to 10 mm within the JRFZ. All fracture and fault traces have consistently sharp margins, juxtaposing unfractured and unmineralized host granodiorite next to highly altered material within the fracture or fault trace.

The dominant set of fracture and fault traces within each fault zone, as well as all right-stepping fractures and faults, extends in a southwest-to-northeast direction with dip directions −80° to the southeast. In contrast, left-stepping fracture and fault traces dip −80° towards the northwest. Left-lateral slip is the dominate sense of movement along the three fault zones; therefore, a relationship between the overall direction of slip along a fault zone and the dip direction of particular fracture and fault surfaces might exist. The non-vertical fault orientation may reflect tilting of the Lake Edison Granodiorite during the late Cretaceous uplifting of the Sierra Nevada batholith.

Fracture and fault traces exposed in the vertical plane may or may not be surrounded by an array of subsidiary fractures. These subsidiary fractures are discrete traces and may be oriented parallel, subparallel, or obliquely to the main fracture or fault trace. The subsidiary fractures tend to interact with both the main fracture or fault trace and each other. The subsidiary fractures have smaller widths than the main fracture or fault trace, ranging from 1 to 4 mm wide.

Fracture traces terminate as a junction with another fracture or fault trace, or simply die out at a tip on the outcrop (Tables 1 and 4). Fault traces may terminate at a junction, as a splay fracture, as a horsetail splay, or die out at a tip (Tables 1 and 4).
Termination as a splay fracture or as a horsetail splay is rare (< 5%). Splay fractures and horsetail splays strike away from the fault traces at angles ranging from 10° to 60°.

Fracture and fault traces interconnect by way of junctions, crossovers, steps, or stepovers. Junctions are the most common, followed by steps, stepovers, then crossovers. The angles between branching traces at junctions range from 10° to 80°. Junctions have a range of complexity, from the simple branching of another fracture or fault trace to having splay and subsidiary fractures within and surrounding the junction. All crossovers have the splay and subsidiary fractures associated with complex junctions. Stepovers may or may not have splay or subsidiary fractures within their structure. Steps consist of a single fracture or fault trace with a consistent width along their length. Steps branch away from their connecting trace at angles between 10° to 40°. The amount of slip along a fault trace does not influence the level of complexity within a junction, crossover, or stepover.

**Slip.** Slip is not uniformly distributed along individual fault traces. Displacement-length profiles typically have steep displacement gradients from the endpoint of the fault trace (Figs. 31 and 49). The slope of the displacement-length profile decreases as the fault trace continues away from the offset closest to the endpoint (Figs. 31 and 49). The displacement-length profile along the entire length of a fault trace may have an irregular shape with more than one peak (Fig. 44).

The distribution of offsets across individual faults within the BCFZ and LCFZ is not uniform, but irregular along both fault zone (Figs. 32a and 45a). The cumulative displacement-length profiles of these two fault zones have irregular shapes and steep displacement gradients at the ends of the fault zones (Figs. 32b and 45b). The boundary faults defining the simple fault zones accommodate only a small fraction (~8 to 10%) of the total offset within the BCFZ. The displacement-length
profile of the JRFZ also has an irregular shape (Fig. 48), but is difficult to interpret because the endpoints of the JRFZ are artificial.

Multiple types of deformation zones (i.e., gouge zones, cataclasite zones, and breccia zones) present within a fault trace at the microscopic-scale suggest that episodic brittle fracturing has occurred along faults within the BCFZ. Ductile deformation on a local scale within the BCFZ is indicated by the presence of mylonitic fabrics observable in thin-sections. At the outcrop-scale within the LCFZ, ductile deformation is indicated by the smearing of dike traces at their intersection with fault traces.

The presence of foliated and nonfoliated gouge zones, as well as foliated cataclasite zones, in thin-sections suggest that a brittle strain softening process has occurred along faults within the BCFZ. The fine-grained nature of the gouge and cataclasite zones is typical of fault zones that have experienced tens of meters to kilometers of slip, but the BCFZ has only experienced relatively small amounts of slip (<6 m) along its trace. Thus some process in addition to slip may be responsible for the production of fine-grained gouge and cataclasite zones.

Mineralization. Hydrothermal mineralization and alteration within fracture and fault traces is widespread, but is not present within all the traces. There is no consistent pattern as to the thickness, composition, or location of mineralization along a particular trace. Chlorite-epidote mineralization is the most common type within all three fault zones. Quartz mineralization is present, but it is not as widespread and is generally restricted to elliptically-shaped pockets within fault traces. Chlorite-epidote mineralization is pervasive within fracture and fault traces in the vertical plane, but quartz mineralization is absent.

Episodic hydrothermal mineralization and alteration is indicated by the presence of multiple shades of mineralized material within the fracture and fault
traces at the outcrop-scale. Thin-section analysis of samples collected from within the BCFZ verifies the existence of multiple hydrothermal mineralization and alteration zones in fractures and faults. Assuming that there is a relationship between episodic mineralization and slip events, then thin-section analysis suggests that a minimum of three slip events occurred within the BCFZ.

Typically surrounding the fracture and fault traces on the outcrop-scale are zones of discolored host granodiorite. These altered zones extend away from the fracture and fault traces for several centimeters. Thin-section analysis indicates that partial alteration of plagioclase grains to an unknown substance within the host granodiorite is responsible for this discoloration.

**Hydrogeology.** The scarcity and randomness of quartz mineralization relative to the widespread distribution of chlorite-epidote mineralization suggest that the fractures and faults within the fault zones have interconnected to such a degree as to be through-going passageways for hydrologic fluids. Both outcrop- and microscopic-scale investigations suggests that junctions and crossovers are important to the overall hydrologic connectivity of a fault zone.

The intermingling of the fractured rock with the products of hydrothermal mineralization and alteration in thin-sections suggest that fluid flow occurred either simultaneously, or shortly after, faulting. In addition, microfaults within fracture and fault traces may impede or redirect fluid flow along fracture and fault surfaces.
THREE-DIMENSIONAL REPRESENTATION
OF FAULT ZONES

A primary goal of this investigation is to supply the geometric and geologic information about fault zone structure in order to construct a three-dimensional representation of that fault zone and to develop ways to approach the general problem of getting three-dimensional shapes from two-and-a-half dimensional data. The three-dimensional depiction, along with field observations, will provide the geologic constraints for spatial statistical and stochastic modeling of how fault zones nucleate and propagate in three dimensions, as well as the distribution of flow paths and permeabilities within the fault zones. This section presents the specifications for the three-dimensional depiction of the three fault zones investigated for this study. First, an overview of the three-dimensional representation and modeling process is given. Then a discussion of important field observations that impact the three-dimensional mechanical modeling of the fault zones is presented. Finally, contraints on modeling parameters will be given.

Once the position and elevation data of the fracture, fault, and dike traces comprising a fault zone are input to a software package first developed by Zheng (1995) and modified by J. Yang on an SGI Graphics work station, a computer-generated depiction of that fault zone is created. The resulting representation is a color-coded three-dimensional “ribbon diagram” of the fault zone that can be manipulated in space to view the fault zone at any angle. The color of each ribbon represents a particular type of fracture, fault, or dike trace, and is explained in Table 6. Examples of these three-dimensional representations for each of the fault zones are shown in Figure 52.

The three-dimensional depiction of a fault zone will provide an important
TABLE 6. FRACTURE, FAULT, AND DIKE TRACE COLOR-CODES

<table>
<thead>
<tr>
<th>Trace</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed fracture or fault</td>
<td>Yellow</td>
</tr>
<tr>
<td>Covered fracture or fault</td>
<td>Green</td>
</tr>
<tr>
<td>Uncertain fracture or fault</td>
<td>Orange</td>
</tr>
<tr>
<td>Covered uncertain fracture or fault</td>
<td>Blue</td>
</tr>
<tr>
<td>Exposed dike</td>
<td>Red</td>
</tr>
<tr>
<td>Covered dike</td>
<td>Light blue</td>
</tr>
<tr>
<td>Uncertain dike</td>
<td>Pink</td>
</tr>
</tbody>
</table>

tool for testing three-dimensional mechanical and stochastic models formulated to describe fracture systems and fluid flow characteristics at depth. Currently, comparisons between field observations and three-dimensional mechanical fault-growth modeling are done with fault data collected by Evans et al. (1996), Lim and Evans (1997), and Lim (1998). An example of such a comparison is shown in Figure 53. In this example, a single fault trace with splay fractures at both endpoints mapped in the field is combined with the results of a computer-generated model of what the three-dimensional structure of that trace should look like, thereby providing a direct comparison between the field data and the model prediction.

Similar comparisons will be done with the field data collected for this investigation to determine the three-dimensional structure of a fault zone. However, current three-dimensional modeling is currently applied to only individual, non-interacting fracture and fault traces. Modeling of the three fault zones investigated here will involve a substantial increase in both scale and complexity. As a result, several characteristics seen in the field need to be addressed before such three-dimensional modeling can be undertaken. One such characteristic is the long lengths of some fracture and fault traces. A decision whether to model these traces as a single fracture or fault surface at depth, or as a combination of several discrete
Figure 52. Computer representation of the three-dimensional structure of the three fault zones. Ribbon colors are explained in Table 6. (a) Bear Camp Fault Zone viewed at S50°E. (b) Lower Camp Fault Zone viewed at N40°E. (c) Jim's Ridge Fault Zone viewed at N30°W.
surfaces that coalesce in such a way that they resemble a single trace on the outcrop, is required. If the latter option is chosen, the location where the surfaces join will need to be established before three-dimensional modeling can proceed.

In addition, how the interaction between fracture and fault traces are to be modeled needs to be addressed. Interactions between traces within the fault zones are accommodated primarily by junctions between traces, steps, and transfer fractures. Splay or subsidiary fractures are located at some junctions, but not at every junction. Thus the three-dimensional model must be able to differentiate between different styles of junctions. Furthermore, steps, stepovers, and transfer fractures could be modeled as either splay fractures or as discrete fracture surfaces.
Again, the modeling will have to incorporate the possible dual nature of these structures. Currently, three-dimensional modeling assumes that a fault surface has splay fractures surrounding the circumference of the fault surface. However, the model will need to take into account those fault traces that do not have splay fractures or horsetail splays at their endpoints.

Three-dimensional modeling is currently applied to fault traces exposed on relatively flat surfaces. In contrast, the three fault zones investigated for this study have substantial elevation changes along their traces. Thus the three-dimensional modeling will need to consider the effects of changing elevation, occurring not only along individual fracture and fault traces, but along the trace of the fault zones in general.

The distribution of slip within a fault zone is crucial to any model of that fault zone because slip indicates the amount and direction of growth within the fault zone. Slip variation along all three fault zones investigated for this study is irregular along individual fault traces, as well as the fault zone traces in general. Furthermore, slip varies across the width of both the BCFZ and LCFZ. Thus any three-dimensional modeling will need to incorporate this nonuniform distribution of slip along fault surfaces and fault zones.

The presence of simple fault zones will require special consideration when modeling the BCFZ. The simple fault zones are relatively discrete units, with boundary faults enveloping regions of internally fractured rock. Therefore, the mechanical modeling must consider not only the formation and growth of these discrete units, but also how the development of these simple fault zones affects the development of the fault zone in general. The same considerations will be required for modeling the fault step complexes found within the BCFZ and LCFZ.

The three-dimensional representation of the fault zones depicts the fracture,
fault, and dike surfaces as vertical planes. Segall and Pollard (1980) have suggested that fracture segments, even discontinuous ones, may coalesce into a single surface at depth (Fig. 54). Furthermore, the palm tree structure within the LCFZ (Fig. 38) also indicates that some fracture and fault surfaces may merge into a common surface. The possible interconnectivity of fracture and fault surfaces at depth may have a substantial affect on fault zone geometry, growth, and hydrologic flow. As a result, the three-dimensional modeling of the fault zones needs to consider the possibility that fracture, fault, and dike surfaces interact at depth, and how to determine where such interaction occurs.

The above discussion presents important considerations raised by this investigation that will need to be addressed before three-dimensional modeling of the fault zones can be undertaken. The field data also provide specific constraints on parameters to be used for modeling these fault zones. One such parameter is the overall nature of fracture and fault traces. In addition to being long and linear, the width of a trace varies along its length by 1 to 40 mm. Furthermore, the widest part

Figure 54. Drawing showing the possible coalescence of individual fault traces at depth. From Segall and Pollard (1980).
of the trace does not necessarily coincide with the centerpoint of the trace length. The spacing between fracture and fault traces is variable, with no consistent pattern (Figs. 15 and 36). However, ~75% of all the traces are separated by 2.5 m or less.

The field data also constrain the nature of fracture and fault trace interaction. In 50 to 70% of all cases, the endpoint of a fracture or fault trace is a junction with another trace (Tables 1 and 4). Furthermore, the angle between the separating traces range from 10° to 80°, with most angles being 30° to 50°. Step fractures form angles of 10° to 45° to their connecting non-coplanar traces. Stepover structures have connecting fractures that form angles between 15° to 30° to the intersecting traces. Finally, fractures within the fault step complexes branch away from the through-going faults at angles of 64° to 90°.

As for how fracture and fault traces terminate, the field data constrains any model to having most of the traces terminating by simply dying out at a tip (Tables 1 and 4). Splay fractures and horsetail splay structures will be limited to ~5% of all fault terminations. Splay fractures branch away from the main fault trace at angles of 10° to 60°.

Further modeling constraints supplied by the field data include the change in left-stepping fracture and fault surface orientation relative to the overall fault zone (Fig. 12b). Multiple flow periods during fault zone development are indicated by the presence of episodic mineralization along fracture and fault traces.

Several aspects of modeling a fault zone are not constrained by the field data obtained in this investigation. The shape of fracture and fault surfaces at depth could not be determined. In addition, the interconnectivity of the fracture and fault surfaces at depth is not constrained. Nor could the sequence of development for fault step complexes or simple fault zones be determined from outcrop observations.
COMPARISON OF FIELD OBSERVATIONS WITH THEORETICAL FAULT-GROWTH MODELS

The primary goals of this investigation are (1) to provide field-based information on the geometry, geology, mineralogy, slip distribution, slip history, and hydrogeologic flow, in and along a fault zone in order to facilitate a three-dimensional representation of the fault zone, and (2) to compare the geometry of the fracture and fault traces comprising a fault zone with the geometry predicted by previous models of fault growth. Previous investigations have used laboratory experiments (Lawn and Wilshaw, 1975; Broek, 1986; Cox and Scholz, 1988; Reches and Lockner, 1994; Moore and Lockner, 1995), analog modeling (Smith and Durney, 1992; Schreurs, 1994; An and Sammis, 1996), field studies (Segall and Pollard, 1983b; Martel et al., 1988; Martel, 1990; Scholz et al., 1993; Dawer and Anders, 1995), and theoretical studies (Martel and Pollard, 1989; Cowie and Scholz, 1992a, 1992b) to explain how faults nucleate and propagate to form fault zones. The implications of my field observations on these fault-growth models will be presented in the Discussion section.

This comparison section begins with a brief overview of the theoretical fault-growth models. Then the geometry and characteristics of fracture and fault traces predicted by these models will be compared to the field observations. This section concludes with a summary listing the results of this comparative analysis.

Overview of Models

There are three models explaining the nucleation, growth, and interaction of faults. The fracture linkage fault-growth model states that the faults form by the coalescence of pre-existing joints (Mode I fractures) by splay fractures (Fig. 55) (Segall and Pollard, 1983b; Martel et al., 1988; Martel and Pollard, 1989; Martel,
Figure 55. The fracture linkage model from Martel (1990).
(a) Formation of joints favorably oriented to the direction of the maximum compressive stress. (b) Shear motion and formation of small faults along pre-existing joints after reorientation of the stress field.
(c) Formation of simple fault zones. (d) Formation of complex fault zones.
1990). Further linkage between faults may eventually form simple, then complex fault zones (Martel et al., 1988; Martel, 1990). The process zone fault-growth model suggests that a fault grows by the in-plane propagation of shear fractures nucleated from tensile fracture arrays (Fig. 56) (Cox and Scholz, 1988; Scholz, 1990; Cowie and Scholz, 1992a). Thus a fault originates as a small damage zone within the rock, grows with progressive slip, and gradually develops characteristic fault trace features (Scholz, 1990).

Recent analogue models investigating fault patterns produced during strike-slip regimes (Schreurs, 1994; An and Sammis, 1996) have shown that fault trace evolution is a function of progressive strain within the fault zone (Figs. 57 and 58). The results of these experiments are collectively referred to in this study as the shear model and represent a third model for fault growth. Complementing the fault-growth models are several field studies, conceptual models, and laboratory experiments dealing with specific features of the above models.

The fracture linkage model was developed from field observations conducted near this study. This model, proposed by Segall and Pollard (1983b), Martel et al. (1988), and Martel and Pollard (1989), states that a fault zone develops in a multi-stage sequence from preexisting joints (Fig. 55a). These joints form in response to a stress field with the maximum horizontal compressive stress parallel to the joints (Segall and Pollard, 1983a). With a rotation of the stress field, the opposing walls of some joints slip relative to one another, forming small strike-slip faults (Fig. 55b) (Segall and Pollard, 1983b). Significant to this model is the idea that the newly formed faults do not grow in length by propagating as shear (Mode II or III) fractures through intact rock. Instead, faults grow in length by the end-to-end linkage of non-coplanar traces by dilatant (Mode I) splay fractures (Martel et al., 1988). Thus slip is transferred between fault traces via splay fractures located at the ends of the fault
Figure 56. The process zone model. (a) Microcrack array. (b) Application of a stress field, resulting in the formation of tensile fractures, a damage zone, along with the nucleation of a shear process zone. (c) Growth of the damage and shear process zones under shear. (d) Further growth of the process shear zone, producing a wide damage zone at the tips of the shear process zone. Adapted from Reches and Lockner (1994).
traces. Further slip along the combined fault traces will be accommodated by the opening of a rhombic-shaped structure between en echelon fault traces (Segall and Pollard, 1980). Such structures will have opening dimensions equal to the amount of slip transmitted along the fault traces (Segall and Pollard, 1980). With further slip along the combined fault traces, several oblique fractures many link two adjacent parallel to subparallel fault traces side-by-side, forming a simple fault zone (Fig. 55c) (Martel et al., 1988). Linkage of these simple fault zones by later oblique fractures produces a complex fault zone structure (Fig. 55d) (Martel, 1990).

According to the fracture linkage model, fault location and geometry is dependent on the distribution and size of preexisting fractures within the host rock.
Figure 58. Fault trace development from the shear model experiment of An and Sammis (1996). Formation of: (a) Primary shears, (b) Simple faults, (c) Compound faults, (d) Step fractures, and (e) Stepovers. S= shear fractures, Sc= secondary conjugate shear fractures, Ss= secondary shear fractures, T= tensile fracture.
(Segall and Pollard, 1983b). All faults start from preexisting fractures. Thus the beginnings of a fault zone are already in place. All that is required is for the orientation of the stress field to change, thereby causing slip to occur along some of the joints and creating the connecting splay fractures between the newly activated fault traces (Martel and Pollard, 1989).

The process zone model was developed as a result of laboratory experiments in samples of Westerly Granite (Cox and Scholz, 1988; Reches and Lockner, 1994; Moore and Lockner, 1995), and brittle engineering materials (Lawn and Wilshaw, 1975; Broek, 1986), combined with a post-yield fracture mechanics model originally proposed by Dugdale (1960). This model proposes that faults first nucleate as a series of tensile (Mode I) fracture arrays (Fig. 56a). These tensile fractures may initially be microcracks between individual mineral grains oriented roughly parallel to the direction of maximum compressive stress within a rock (Moore and Lockner, 1995), microcracks that nucleate at the tips of favorably oriented mica grains (Gottschalk et al., 1990), or microcracks that develop at the tips of pre-existing slots within laboratory samples (Cox and Scholz, 1988). With increasing stress, a few of these microcracks interact by enhancing the dilation of one another, producing a damage zone within the host rock (Fig. 56b) (Reches and Lockner, 1994). A through-going shear discontinuity (Mode III fracture), called the shear process zone, will form if the damage zone is concentrated enough and is oriented 20° to 30° to the maximum compressive stress (Fig. 56b) (Cox and Scholz, 1988; Reches and Lockner, 1994). Once the shear process zone is established, the zone acquires the characteristics of a fault surface and becomes the source for the subsequent generation of tensile fracture near the ends of the fault (Fig. 56c) (Cox and Scholz, 1988). When sufficient deformation has occurred among the tensile fractures at the ends of the fault, the fault surface propagates into the weakened damage zone and the
process repeats itself (Fig. 56d) (Scholz, 1990). As the fault surface accumulates displacement, frictional wear will smooth out the irregularities resulting from the incorporation of the damage zone and an intermittent layer of gouge forms (Cowie and Scholz, 1992a). Eventually, a well-developed fault surface that resembles an established through-going fault forms (Cowie and Scholz, 1992a).

The process zone model envisions the growth of a fault as a progressive process (Scholz, 1990). As a result, this model predicts two characteristic features. First, that the slip distribution along an individual fault trace is cumulative, with the maximum slip occurring near the center of the fault trace and tapering off to zero at the tips (Scholz, 1990; Cowie and Scholz, 1992a). Thus a displacement-length profile along a fault trace will consist of a symmetrical bell-shaped curve (Scholz, 1990; Cowie and Scholz, 1992a; Dawers et al., 1993). The second characteristic feature predicted by this model is that a zone of deformation will be present adjacent to the fault trace and surrounding the tips of the fault trace. The size of the deformation zone scales upwards in width and length as displacement along a fault trace increases, thereby producing a deformation zone much wider than the well-developed fault trace (Scholz, 1990; Cowie and Scholz, 1992a). As the fault trace advances into the deformation zone, the tensile fracture array within the deformation zone is destroyed and a smooth through-going fault trace forms (Bjarnason et al., 1993; Reches and Lockner, 1994; Moore and Lockner, 1995).

The shear model experiments of Schreurs (1994) and An and Sammis (1996) examined the development of strike-slip fault geometries under distributed shear deformation. Schreurs (1994) used an apparatus containing a layer of thin Plexiglass bars stacked as cards between the moving and fixed base plates and the sample material. The sample material consisted of a thin layer of viscous PDMS elastomer overlaid with alternating layers of dry quartz sand and glass powder (Schreurs, 1994).
During the experiment, Schreurs (1994) documented that shear deformation is first accommodated by the formation of major synthetic strike-slip faults (master faults) oriented at an angle between 23° and 35° to the applied shear direction (Fig. 57a). As strain increases, the master faults remain active while two new sets of faults form. These faults included synthetic strike-slip faults (secondary faults) striking at lower angles than the previously formed master faults, and arrays of evenly spaced antithetic strike-slip faults (cross faults) striking at ~60° to the shear direction (Fig. 57b) (Schreurs, 1994). Schreurs (1994) noted that during the course of the experiment the cross faults accommodated minor strike-slip displacement, acquired a sigmoidal shape in map view, and developed a small dip-slip component along strike (Fig. 57c). In addition, the cross faults either merged into or terminated at master or secondary faults (Fig. 57d) (Schreurs, 1994). Schreurs (1994) explained the resulting fault geometry by suggesting that the master faults alter the local stress field, thereby determining the orientation of subsequent faults, which generally do not appear until after the master faults have developed.

The An and Sammis (1996) experiment differs from the experiment of Schreurs (1994) in that they attempted to generate fault geometries at relatively large strains in order to represent natural shear deformation which produces significant displacements along fault traces. Furthermore, An and Sammis (1996) used gravity sliding to achieve shear deformation as opposed to the moving base plate of Schreurs (1994). An apparatus consisting of an aluminum board with an axle allowing tilting at any angle up to 90° was covered by a sheet of plastic wrap (An and Sammis, 1996). A thin layer of water was placed over the plastic wrap and the sample material, a combination of fault gouge taken from along the San Andreas and San Gabriel faults and clay, was placed over the plastic layer (An and Sammis, 1996). The board was then tilted to produce shear deformation within the sample material.
An and Sammis (1996) documented that faults nucleated on either pre-existing pores or on low-displacement protofaults in flaw-free areas. A small number of these pores and protofaults developed significant displacement and grew in conjugate shear directions, forming primary shears (Fig. 58a) (An and Sammis, 1996). Once formed, some of the primary shears propagated in-plane as simple faults, with the remaining primary shears and protofaults being abandoned (Fig. 58b) (An and Sammis, 1996). An and Sammis (1996) noted that small simple faults terminated by dying out at a tip, with a splay fracture, or with an en echelon fracture array, whereas large simple faults terminated with a horsetail splay structure.

As the simple faults grow in length and approach one another, they begin to interact and coalesce to form longer compound faults (Fig. 58c) (An and Sammis, 1996). As two parallel, but non-coplanar, fault traces approached one another, An and Sammis (1996) noticed that secondary shear fractures, secondary conjugate shear fractures, or tensile fractures developed between the fault tips (Fig. 58d). These fractures connected the two faults together, forming steps. If the two fault traces extended beyond each other, multiple shear, conjugate shear, or tensile fractures developed within the space between the two faults and a stepover structure was produced (An and Sammis, 1996). An and Sammis (1996) noted that the geometry of the stepover structure was dependent on the type of fractures forming the stepover as well as the direction the stepover grew (Fig. 58e). If a stepover consisted of conjugate shear or tensile fractures connecting the fault traces to one another (type I structure), the stepover has a short and wide shape, and grew parallel to the fault strike (An and Sammis, 1996). However, if the stepover consists of shear fractures connecting the fault traces together (type II structure), the stepover had a long and narrow shape, and grew oblique to the fault strike (Fig. 58e) (An and Sammis, 1996).
Once formed, compound faults continued to propagate as a single fault trace or coalesced with other faults (An and Sammis, 1996). Where numerous strike-slip faults compete to grow by propagation and coalescence, An and Sammis (1996) documented that one fault emerged with the fastest growth rate and spanned the region to become a through-going shear zone. Once this through-going shear zone was established, deformation within the sample material became nonuniform (An and Sammis, 1996).

The shear model experiments predict that faults can propagate in-plane as shear (Mode II or III) fractures independent of tensile (Mode I) fracturing (An and Sammis, 1996). Furthermore, the development of fault traces affect the local stress field, thereby affecting the nucleating and propagation of later faults within the fault zone (Schreurs, 1994; An and Sammis, 1996).

**Comparison of Field Observations with Model Predictions**

For the comparative purpose of this study, specific features of my field observations will be compared to each fault-growth model separately. First, the characteristics of those fracture and fault traces that I investigated are compared to those predicted by the fault-growth models. This is followed by the characteristics of the connecting structures between individual traces. The characteristics of the simple fault zones are then compared with the observations of Martel et al. (1988), who originally defined and described simple fault zones. This is followed by a listing of those features I documented in the field that are not addressed by any of the fault-growth models. This section concludes with a summary of my comparison results.

The fracture and fault traces within all three fault zones in the study area are linear, and are separated from one another by relatively unfractured areas of rock that are much longer than they are wide. The fracture and fault traces are tens of meters
long and typically are parallel to subparallel to one another. Furthermore, the traces maintain consistent widths between one another along their lengths. All three fault-growth models predict that fault traces will have characteristically linear traces surrounding regions of intact rock. The fracture linkage model and the shear model experiments indicate the presence of long fault traces, but only the fracture linkage model gives an actually length: tens of meters to kilometers long. No fault trace length is specified by the process zone model. However, the process zone model states that the predictions of the model are not scale dependent (Scholz, 1990). Therefore, a fault trace may range from millimeters to kilometers in length. The consistent distance between parallel fracture and fault traces within the three fault zones is similar to the predictions of the fracture linkage model (Fig. 55) and the results from the shear model experiments (Figs. 57 and 58). Furthermore, this consistent width between fractures and fault traces within a fault zone is also present between the fault zones within the study area (Fig. 2).

In the process zone model, slip is distributed symmetrically along the length of a fault trace, resulting in a smooth displacement-length profile (Scholz, 1990; Cowie and Scholz, 1992a; Dawers et al., 1993). Thus the amount of slip at a point along a fault trace is related to its position along the fault trace and is maximum near the middle of the fault trace. Such a relationship is not found along any of the fault traces that I investigated because slip is scattered within the fault zones (Figs. 32a and 45a). As a result, the fault zones have irregular displacement-length profiles (Figs. 32b, 45b, and 48). Cowie and Scholz (1992a, 1992b) have attempted to explain discrepancies between the process zone model predictions and field observations like those documented in this study by suggesting that a symmetric displacement-length profile is only obtained along individual fault traces. Once fault traces interact and coalesce, the displacement-length profile will have an irregular
shape (Cowie and Scholz, 1992a, 1992b). Only one of the fault traces that I investigated, fault 4 within the LCFZ, does not interact with another fracture or fault trace. This fault trace does not have a symmetric displacement-length profile (Fig. 44). Willemse (1997) and Cartwright and Mansfield (1998) have suggested that irregular displacement-length profiles are the result of the interaction between overlapping, but not connected, fault traces. In addition, Cowie and Scholz (1992b) and Willemse (1997) suggest that the displacement is not distributed equally along the fault surface. Therefore, the position of a fault trace within the vertical plane of the fault surface may affect the displacement-length profile of the fault trace (Cowie and Scholz, 1992b; Willemse, 1997). Because I have no way of knowing where these fault traces lie within their respective fault surfaces, this key characteristic of the process zone model cannot be compared with my field observations.

Results from the shear model experiments indicate that linear fault traces will nucleate and propagate to great lengths before the nucleation of secondary faults, which also tend to have long, linear traces. The geometric pattern of the fracture and fault traces I investigated match relatively well to the pattern developed in the Schreurs (1994) experiment.

The fracture linkage and process zone models make different predictions concerning the thickness of a fracture or fault trace. The fracture linkage model states that the thickness of a fault trace is not uniform along strike due to slip nucleating at certain points along the trace instead of occurring simultaneously along the entire trace length (Martel and Pollard, 1989). In contrast, the process zone model predicts that the thickness of a fault trace will increase as slip progressively accumulates (Scholz, 1990). Thus the center portion of a fault trace will be the thickest because that is the oldest part of the trace and has, therefore, experienced the most slip (Scholz, 1987; Scholz, 1990). The farther away from the center of the fault
trace, the thinner the trace is predicted to be and eventually the thickness of the
trace becomes zero at the tips (Scholz, 1990). Because the predictions of the process
zone model are not scale dependent (Scholz, 1990), the fault zone should be the
widest at its center and taper down in width away from the center of the fault zone.
My field observations showed that the thickness of a fracture or fault trace varies
along the length of the trace. In addition, I found that the amount of slip that had
occurred along a fault trace does not appear to influence the thickness of that trace.
Finally, none of the three fault zones investigated here have the thickness geometry
predicted by the process zone model. The shear model experiments did not address
the thickness of fracture and fault traces, or the overall fault zone.

All of the fracture and fault traces investigated here have a sharp margin
between the trace and the host rock. The fracture linkage model predicts the same
feature. In contrast, the process zone model predicts that a fault trace will be
surrounded by a zone of fractured host rock (Cowie and Scholz, 1992a).
Furthermore, the damage zone will be the greatest surrounding the youngest portion
of the trace because not enough slip has occurred there to smooth the irregularities
associated with brittle fracturing (Dugdale, 1960; Cowie and Scholz, 1992a). This
prediction was confirmed by Chester and Logan (1986), who documented that large
strike-slip faults typically consist of a single, continuous gouge layer bounded by
zones of extensively damaged host rock. Along the small strike-slip faults
investigated in this study, however, there was no damage of the surrounding host
rock. The shear model experiments did not address the condition of the margin
between a fracture or fault trace and the host rock.

According to the fracture linkage model, joints on which shear slip does not
occur remain as Mode I fractures (Segall and Pollard, 1983b). There was no outcrop-
scale evidence for the presence of Mode I fractures within the three fault zones that I
investigated. In addition, microscopic evidence for Mode I fracturing was not present in any of the rock samples collected from within the BCFZ. The lack of Mode I fractures within the three fault zones contradicts previous investigations in which such fractures are widely distributed in the Lake Edison Granodiorite (Segall and Pollard, 1983b; Martel et al, 1988; and Martel, 1990). A possible explanation for this discrepancy is presented in the Discussion section.

The process zone model states that the original tensile (Mode I) fractures are incorporated within the shear (Mode III) process zone, thereby destroying the tensile fractures (Reches and Lockner, 1994; Moore and Lockner, 1995). Thus Mode I fractures should only be preserved at the tips of the fault traces. No tensile fracture arrays resembling those predicted by the process zone model were found at or near any of the fault tips within the three fault zones.

Only the process zone model addresses the characteristics of a fracture or fault trace in the vertical plane. According to Cox and Scholz (1988), a fault surface mapped as a single trace along the outcrop surface is actually surrounded by an extensive zone of fracturing at depth. Where a vertically exposed fracture or fault trace is present, the trace is either surrounded by a network of subsidiary fractures, as predicted by the process zone model, or may exist as a single trace. The process zone model also suggests that the thickness of the fracture or fault trace will increase with depth if the host rock remains uniform in composition (Cox and Scholz, 1988; Scholz, 1990). The thickness of the fracture and fault traces that I investigated remained relatively constant in the vertical plane. However, the thickness of a trace in the vertical plane may be a function of the three-dimensional structure of the fracture or fault surface. The vertical exposures used by Cox and Scholz (1988) to formulate their prediction extend for hundreds of meters, whereas the vertical exposures I investigated do not extend for more than 3 m. Thus comparison between
my observations and features predicted by the process zone model may not be appropriate because of this difference in scale.

My field observations document that a fault trace may terminate in a number of styles. Furthermore, some fault traces may have similar termination styles at both tips whereas other fault traces have different combinations. Such variations in termination styles exist along the tips of normal faults investigated by Cartwright and Mansfield (1998). All the fracture traces that I investigated terminated by simply dying out at the tip. Fault traces terminated as a splay fracture, a horsetail splay structure, or by dying out at the tip. According to the fracture linkage model, only joint traces will die out at a tip, whereas fault traces may terminate as a splay fracture, a horsetail splay structure, or as a zone of foliated rock (Segall and Simpson, 1986; Bürgmann and Pollard, 1994). Splay fractures and horsetail splay structures were found at the tips of fault traces within the three fault zones that I investigated, but the occurrence of these structures are rare compared to fault traces simply dying out at a tip (Tables 1 and 4). Where fault traces terminated by dying out at a tip, no zone of foliation was present.

The array of tensile fractures surrounding the tips of fault traces predicted by the process zone model is not present in the study area. Cox and Scholz (1988) suggest that if the tensile fractures grow long enough, they would resemble a splay fracture or horsetail splay structure. Thus the splay fractures and horsetail splay structures I documented within the three fault zones may have originally been such tensile fractures.

Termination styles of faults were not addressed in the shear model experiment of Schreurs (1994). However, the shear model experiment of An and Sammis (1996) produced fault traces that terminated as an en echelon fracture array, a horsetail splay structure, or by dying out at the tip. Only the en echelon fracture array style was not
developed in the study area.

The different styles of fault termination, as well as which style occurs at the tip of a fault trace, are an integral part of a three-dimensional fault surface model proposed by Martel (1997) and Martel and Boger (1998). Cartwright and Mansfield (1998) documented from field investigations that there is no correlation between specific termination styles and fault parameters (i.e., displacement-length relationships, fault thickness, slip amount) or rock types. Therefore, some unspecified feature constrains the style in which a fault terminates. Martel and Boger (1998) suggest that the variation in termination styles is related to the three-dimensional structure of the fault surface. Using a cohesive zone model applied to an elliptically-shaped fault surface, Martel and Boger (1998) produced a geometric model in which the type of secondary fracture present along the circumference of the fault surface determines the fault termination style (Fig. 59). Thus the style in which a fault trace terminates along the outcrop is a function of the fault traces position in the three-dimensional surface of the fault (Martel and Boger, 1998). This model may explain the variation in and distribution of termination styles documented by my field data.

The geometric model of Martel and Boger (1998) may also explain the presence of the zipper-like fracture pattern found within the BCFZ (Fig. 19). This fracture pattern, consisting of a central fracture trace traversing across an array of en echelon fractures, resembles the O-shaped secondary fractures of Martel and Boger (1998) located at the 6:00 position (Fig. 59). Thus some characteristics of fracture or fault traces may indicate where the trace is located along the three-dimensional surface of the fracture or fault.

A large discrepancy exists between my field observations and both the fracture linkage and process zone models concerning the geometry of fracture and
fault linkage and interaction. My field data suggest that fracture and fault traces link
together either at a junction or end-to-end by way of step fracture or stepover.
These steps, as well as the stepovers, consist of single, discrete fractures. The
fracture linkage model states that fault traces are joined by splay fractures, or by a
horsetail splay structure (Fig. 55b) (Martel et al., 1988). Two-dimensional clay
model experiments by Pollock and Evans (1996) produced splay fractures which
joined parallel fault traces to one another as predicted by the fracture linkage model.
A splay fracture might resemble the step fractures within the fault zones, but no
horsetail splay structures connected two fault traces to one another. Another
prediction of the fracture linkage model is that the splay fractures linking individual
fault traces together nucleate at the trace tips and propagate towards each other (Segall and Pollard, 1983b; Martel et al., 1988). As a result, the thickness of these splay fractures will be the greatest near the fault tips and decrease as the splay fractures extends away from the fault tip (Segall and Pollard, 1983b). In contrast, the thickness of the faulted rock within the step fractures was fairly consistent along the entire length of the step. Furthermore, the clay model experiments of Pollock and Evans (1996) documented that splay fractures may nucleate at the fault tips and then grow towards one another, or nucleate between the fault tips and propagate towards the tips of the faults. Thus unilateral fracture propagation from a fracture tip is not always the case.

The fracture linkage model predicts that a rhombic-shaped stepover containing multiple secondary fractures will form as the splay fractures open in response to continued slip along the connected en echelon fault traces (Segall and Pollard, 1983b). Secondary fractures were present within some of the stepovers that I investigated, particularly those stepovers within the LCFZ (Fig. 38), but the majority of the stepover structures lacked secondary fractures.

The process zone model suggests that some of the en echelon tensile fractures at the tips of a fault trace will propagate as Mode I fractures and connect two non-coplanar fault traces to one another, producing a splay fracture or horsetail splay structure (Cox and Scholz, 1988; Scholz, 1990). As with the fracture linkage model, the linkage geometry predicted by the process zone model does not specifically match my field observations. The development and geometry of stepovers is addressed by the process zone model for only fault zones that are hundreds of meters to kilometers in length (e.g., Scholz, 1990; Scholz et al., 1993; Dawer and Anders, 1995). Although the process zone model is not scale dependent (Scholz, 1990), the geometry of the fractures comprising the natural stepovers investigated by Scholz et
al. (1993) and Dawer and Anders (1995) does not resemble my field observations.

The shear model experiment of Schreurs (1994) does not address the linkage and coalescence of individual fault traces beyond the formation of secondary faults branching off from the master faults. In contrast, the experiment of An and Sammis (1996) produced both step and stepover structures. As with the An and Sammis (1996) results, my field data documents that step fracture traces connect with, and terminate at, the tips of non-coplanar fracture or fault traces. However, I was not able to ascertain whether such step fractures originally formed as shear, conjugate shear, or tensile fractures. Both the type I and type II stepover structures produced during the An and Sammis (1996) experiment are present within the BCFZ and the LCFZ. The stepover structure within the JRFZ resembles the type I structure of An and Sammis (1996).

Some splay fractures exist between and connect together non-parallel fault traces, but are not located at the fault tips (e.g., those fractures between faults 12 and 13 within the BCFZ). None of the three fault-growth models address this type of splay fracture. Mechanical modeling by Cooke (1997) suggests that variations in frictional strength anywhere along a fault trace can produce slip gradients and stress concentrations which will promote single or multiple splay fracture localization inwards from the fault trace tips. The random distribution of chlorite-epidote mineralization and the variation in fault-gouge formation within the fault traces I investigated could vary the frictional strength along the traces, thereby promoting or restricting localized splay fracture formation.

Transfer fractures are common within the BCFZ, but are absent in the LCFZ and JRFZ. The characteristics of transfer fractures are not addressed in the process zone model, nor are they dealt with in the fracture linkage model except when discussing simple or complex fault zones. The cross faults which nucleated and
propagated between existing master and secondary fault traces documented in the shear model experiment of Schreurs (1994) have the same geometry as the transfer faults present within the BCFZ. Furthermore, the curvature and change in dip angle along strike of these cross faults noted by Schreurs (1994) are characteristic of some of the transfer faults. An and Sammis (1996) did not specifically mention the development of fractures resembling transfer fractures. However, the geometry of the conjugate shear or tensile fractures noted by An and Sammis (1996) could resemble the geometry of the transfer fractures that I investigated.

Only simple fault zones were found during my field investigation and these simple fault zones were restricted to within the BCFZ. Simple fault zones are an integral part of the fracture linkage model and their characteristics were documented during field investigations conducted south of the BCFZ by Martel et al. (1988). Complex fault zones, the final stage of the fracture linkage model and present throughout the Bear Creek region (e.g., Martel, 1990), are absent in the three fault zones I investigated. The process zone and shear model experiments do not address the formation or characteristics of simple fault zones. The geometry and overall characteristics of the simple fault zones that I investigated compare relatively well to Martel et al. (1988). However, there are several discrepancies between my field data and those of Martel et al. (1988).

According to Martel et al. (1988), the boundary faults defining the edges of the simple fault zones are wider and accommodate more displacement than the other fault traces within the overall fault zone. A direct comparison between my field observations to the thickness claim of Martel et al. (1988) is not possible because I have only minimum values for the thickness of the boundary faults. However, the minimum trace width of the boundary faults that I investigated does not exceed the maximum trace thickness within the BCFZ. No dike traces are offset along the
eastern simple fault zone, making a comparison with the suggestion that the displacement is greatest along the boundary faults impossible. On the other hand, dike traces are offset along the boundary faults of the western simple fault zone. The amount of offset along these boundary fault traces indicates that, contrary to Martel et al. (1988), slip is not a maximum along the boundary faults. Instead, the greatest amount of slip within the BCFZ occurs along fault traces between the two simple fault zones.

Martel et al. (1988) state that a boundary fault consists of non-coplanar fault traces joined together by steps or stepovers. I found that only the northern boundary fault of the western simple fault zone has such a feature along its trace (Plate 1A). The three other boundary faults extend without steps or breaks along their lengths. Furthermore, Martel et al. (1988) suggest that boundary fault traces terminate as a splay fracture or horsetail splay structure. In contrast, the boundary faults that I investigated either continued as individual fault traces or disappeared beneath a covered area.

The internal fractures within simple fault zones are classified by Martel et al. (1988) as being either first- or second-order fractures. The first-order fractures intersect, but do not cross, the boundary faults and typically extend the width of the simple fault zone (Martel et al., 1988). These first-order fractures resemble the transfer fractures within the eastern simple fault zone. The cross fractures that formed during the shear model experiment of Schreurs (1994) also resemble these transfer fractures within the eastern simple fault zone. The second-order fractures are shorter than the first-order fractures, and are usually confined between either two first-order fractures, or between a first-order fracture and a boundary fault (Martel et al., 1988). The small internal fractures present within the western simple fault zone resemble these second-order fractures. However, such fractures are not as pervasive
within the western simple fault zone as within those simple fault zones investigated by Martel et al. (1988). The eastern simple fault zone lacks any internal fractures resembling second-order fractures.

According to Martel et al. (1988), the microscopic fabric of the boundary faults is distinct from that of other fault traces. Specifically, the material within the boundary faults shows a cataclastic fabric whereas the material within other faults is characterized by a mylonitic fabric (Martel et al., 1988). Thin-section analysis of the rock sample from the southern boundary fault of the western simple fault zone suggests that the microscopic fabric of the boundary faults is not different than the fabric in other fracture or fault traces. Mylonitic fabrics are not present within the boundary fault sample, but foliated and nonfoliated cataclastic fabrics are present throughout fracture and fault traces not associated with the simple fault zone. Therefore, the Martel et al. (1988) observation cannot be applied to all the fracture or fault traces within the fault zone.

Several features within the three fault zones that I investigated are not addressed by any of the fault-growth models. Such features include crossovers between fracture and fault traces, the fault step complexes within the BCFZ and the LCFZ, the presence and geometry of the secondary and subsidiary fractures located at junctions between fracture or fault traces, and the change in dip direction of left-stepping transfer fractures relative to the dominate set of fracture or fault traces.

**Summary of Comparison Results**

Provided below is a listing of the results from the comparative analysis between my field observations and the fault-growth models. The implications of this analysis are presented in the Discussion section.

1. All three fault-growth models agree with my observation that fracture and
fault traces are linear features that confine regions of unfractured rock. The consistent distance between the parallel to subparallel fracture and fault traces resembles the prediction of the fracture linkage model and the results of the shear model experiments.

2. The displacement-length profiles of individual fault traces, as well as the fault zones as a whole, investigated for this study do not match the predictions of the process zone model.

3. The thickness of fracture and fault traces is nonuniform along the length of the trace. This observation is consistent with the fracture linkage model, but not the process zone model. The shear model experiments do not address this issue.

4. Fracture and fault traces have sharp margins between the trace and the host rock. Again, this observation is consistent with the fracture linkage model, but not the process zone model. This issue is not addressed by the shear model experiments.

5. Joints (Mode I fractures) interspersed among fault traces as predicted by the fracture linkage model and the shear model experiment of An and Sammis (1996) were not found.

6. The process zone model predicts that tensile (Mode I) fractures will surround the tips of fault traces, and that a zone of damaged host rock will surround well-established fault traces. Neither of these features is present in the fault zones that I investigated.

7. Subsidiary fractures surrounding a fracture or fault trace in the vertical plane as predicted by the process zone model may or may not exist. The suggestion by the process zone model that the thickness of a trace increases with depth cannot be confirmed or denied by my observations.
because the vertical planes I investigated are relatively small. Neither the fracture linkage model nor the shear model experiments address the vertical characteristics of fractures and faults.

8. All three fault-growth models predict that a fault trace may terminate in a variety of styles, but not all of the predicted styles are present in the fault zones that I investigated.

9. The geometry of fault terminations, as well as other fracture trace geometries, resembles the structures predicted by a conceptual three-dimensional fault surface model proposed by Martel and Boger (1998).

10. The predictions of the fracture linkage and process zone models concerning how fracture and fault traces interact and coalesce with one another are not consistent with my observations. However, results from the shear model experiment of An and Sammis (1996) closely match my observations.

11. The transfer fractures found within the BCFZ resemble the cross faults produced during the shear model experiment of Schreurs (1994). Transfer fractures are not addressed in the fracture linkage or process zone models.

12. The overall geometry of the simple fault zones that I investigated matches the observations of Martel et al. (1988). However, specific features of the boundary fault traces, such as their thickness, amount of slip, linkage, termination styles, and microscopic fabric, do not match the model of Martel et al. (1988).

13. Some features found within the three fault zones, such as crossovers, fault step complexes, junction structures, and fault networks, are not addressed in any of the fault-growth models.

14. Overall, none of the three fault-growth models completely explain my field
observations. Instead, specific features of each model match the characteristics or geometries present within the three fault zones that I investigated.
DISCUSSION

In the preceding section, characteristics of the three fault zones investigated for this study are compared to the characteristics predicted by three fault-growth models. In this section, the implications of my field observations, as well as investigations by other researchers, on these fault-growth models are discussed. While none of the three fault-growth models can completely explain all the field observations documented by this investigation, neither can any of these models be dismissed entirely.

This investigation emphasizes the structure of fractures and faults that interact to form fault zones tens to ~100 of meters in length. The nucleation and propagation of individual, noninteracting fractures or faults are not addressed in this study. Similarly, the debate between standard linear elastic fracture mechanics (e.g., Broek, 1986) and the cohesive zone theory (e.g., Martel, 1997) of fault nucleation and growth is not presented here. These aspects of fault-growth modeling are addressed in the companion study by Lim (1998).

This section begins by building on the inference that the faults studied here may have nucleated as in-plane shear fractures. The following discussion about the process zone model is divided into two parts: the implications of my field observations on the geometry and features predicted by the model, and a discussion about the use of displacement-length profiles to predict fault and fault zone development. A discussion of the fracture linkage model follows, which includes an attempt to reconcile the paradox of conflicting field observations from the same study area. The implications of my field observations and those of the shear model experiments on fault-growth modeling are presented next. This section concludes with my suggestion that shear strain (i.e., deformation) and the nonuniform nature
of faulting, two features not included in current fault-growth models, may be important in producing the fault and fault zone geometries documented by this investigation.

Based on theoretical and experimental investigations, the propagation of faults as in-plane shear (Mode II and III) fractures is not considered to be possible (Brace and Bombolakis, 1963). While in-plane propagation of shear fractures has been observed in laboratory experiments by Petit and Barquins (1988), Reches (1988), and Reches and Lockner (1994), the mechanism for such in-plane propagation is the in-plane coalescing of tensile (Mode I) fractures. Both the process zone and fracture linkage models are based on the concept that faults cannot propagate as shear fractures without the nucleation of tensile fractures occurring first. However, evidence for the existence of tensile fractures preceding shear displacement along fault traces is absent at all scales within the fault zones I investigated. Cooling joints, which form as tensile fractures, may have existed within the fault zones, but subsequent slip and hydrothermal mineralization and alteration may have eliminated evidence indicating the presence of tensile fractures at the ends of such joints. During their experiments, An and Sammis (1996) did not observe the formation of tensile crack arrays preceding the propagation of shear fractures during the early stages of fault development. Therefore An and Sammis (1996) conclude that, based on the theoretical work of Melin (1986), in-plane shear propagation can take place independent of tensile fracturing under certain conditions.

An explanation for the possible in-plane propagation of shear displacement along faults suggested by my field data and the results of the shear model experiments of An and Sammis (1996) involves brittle strain softening. During this process, cataclasitic flow within a fault can occur under brittle deformation conditions. The presence of foliated mineralization within the thin-sections I
investigated suggests that brittle strain softening has occurred within the fault zones investigated for this study. Furthermore, brittle strain softening is similar to the strain softening that occurred within the clay material used in the shear model experiments of An and Sammis (1996). Thus very early strain localization and softening along faults may permit the in-plane propagation of faults as shear fractures, and could also explain the absence of tensile fractures and joints within the fault zones that I investigated.

Of the three fault-growth models discussed in this study, the process zone model is least able to match the fault zone geometries I documented. At the microscopic scale, nucleation of faults as predicted by this model cannot be tested against my field observations as none of the rock samples used for thin-section analysis are from the tips of fault traces. However, the process zone model predicts that the microscopic structures associated with fault nucleation and propagation will be destroyed as the fault propagates, making it difficult to verify this prediction at locations other than fault trace endpoints.

An important feature of the process zone model is that the predicted characteristics are independent of scale (Scholz, 1990). Therefore, the same characteristics predicted for the microscopic-scale should be present within fault zones tens of meters to hundreds of kilometers long. These characteristics, such as a damage zone surrounding the trace and tip of a fault, or an en echelon pattern of tensile fractures preceding the connection of two faults, are not present within the fault zones investigated for this study. Interestingly, fault zones at the scale of my investigation have not been specifically dealt with by supporters of this model, other than suggesting that most of the faults seen at this scale were originally tensile fractures that evolved into shear faults through time (Scholz, 1990).

It is the characteristics of fault zones hundreds of meters to kilometers in
length that supporters of the process zone model use to verify this models predictions. One example is the fault zone activated during a 1912 magnitude 7.0 strike-slip earthquake in south Iceland (Einarsson and Eiríksson, 1982; Bjarnason et al., 1993). The style and geometry of surface fracturing produced by this earthquake closely match the pattern predicted by the process zone model for the first stages of shear fracture development (Bjarnason et al., 1993). Furthermore, the surface fracturing pattern resembles those produced at the microscopic scale in the laboratory experiments of Cox and Scholz (1988). The problem with using this particular example is that these fracture patterns formed in fresh basalt flows that cover the strike-slip fault in which the earthquake event occurred along. Thus the surface fractures developed as the result of displacement along a preexisting fault. Furthermore, the laboratory experiments of Cox and Scholz (1988) used rock samples containing preexisting notches from which fractures nucleated. Therefore, the fracture patterns used to support the predictions of the process zone model are actually secondary structures that do not represent true nucleation of a shear fracture system.

Many discrepancies exist between the predictions of the process zone model and the structures found within the fault zones investigated for this study. In addition, the concept that fault nucleation and propagation features are destroyed with progressive slip, as well as the lack of rigorous field investigations of small fault zones, suggests that the process zone model is not useful for describing the development of small-scale fault zones. At larger scales, the process zone model appears to be more appropriate for explaining the development of secondary fractures within rock or soil layers associated with blind faults. Thus this model may be more applicable to specific cases of fault zone development than as a general model for fault growth.
One feature of the process zone model currently receiving a substantial amount of investigation is the use of displacement-length profile analysis to predict fault and fault zone development (e.g., Cowie and Scholz, 1992a, 1992b; Gillespie et al., 1992; Dawers et al., 1993; Scholz et al., 1993; Dawers and Anders, 1995; Nicol et al., 1996; Willemse et al., 1996). The process zone model predicts that a fault maintains a self-similar displacement-length profile through time (Cowie and Scholz, 1992a, 1992b). This prediction is at odds with data from individual faults and fault zones investigated for this study. Instead, the displacement-length profiles here have irregular profiles (Figs. 33, 44, 45, and 48). The prediction that a progressive change of the incremental slip profile occurs during fault growth is not borne out by other field observations on faults in other study areas. Instead, these fault investigations indicate that: (1) displacement decreases more rapidly away from the maximum at the fault center (Gillespie et al., 1992; Willemse, 1997); (2) slip along individual faults is nonuniform along the fault (Walsh and Watterson, 1987; Rymer, 1988; Peacock and Sanderson, 1991); or (3) that the variation in lateral displacement gradients is not related to fault dimension in any obvious way (Cartwright and Mansfield, 1998). Furthermore, Gillespie et al. (1992) found that quantitative slip data do not demonstrate that displacement is constant at all stages of fault growth.

Thus it appears that the nonuniform nature of displacement along fault surfaces limits the usefulness of displacement-length profiles as a general representation of fault or fault zone development.

Further complicating the use of displacement-length profile analysis is determining what scale of observation should be used. A fault trace that is considered to be continuous on one scale may be segmented when observed at a smaller scale, or vice versa (Nicol et al., 1996). Once a fault segment interacts with another, the displacement-length profile becomes irregular (Cowie and Scholz,
This prediction has been verified from field investigations by Cartwright and Mansfield (1998). To eliminate the effects of fault segmentation requires changing the scale of observation so that the individual segments of a long fault or fault zone are combined into a single fault or fault zone trace (Gillespie et al., 1992). At the larger combined scale, the predicted symmetrical displacement-length profile is obtained. The question is how realistic is such an analysis if small-scale features indicative of fault or fault zone growth are eliminated in order to produce a predicted displacement-length profile? Furthermore, if the observation scale of a fault or fault zone is increased, the effects of multiple rock type and tectonic environments may alter the displacement-length profile (Cowie and Scholz, 1992b). Therefore, displacement-length profile analysis should be restricted to faults or fault zones located within a single rock type and tectonic environment, which are more likely to be found in the smaller scale range (Cowie and Scholz, 1992b). The fault zones investigated for this study meet this criterion, but the displacement-length data produced irregular profiles. A possible explanation for this discrepancy is that it is not the scale of observation which governs the displacement-length profile, but the data sets used in the statistical analysis (Gillespie et al., 1992). According to Gillespie et al. (1992), the data sets should span a sufficient range of fault displacement sizes, at least eight orders of magnitudes: from 1 mm to 100 km, to make a displacement-length profile analysis meaningful for predicting fault and fault zone development. Therefore, the accuracy of a displacement-length profile is dependent on the compromise between the effects of using a large scale of observation and having a sufficient range of fault displacement data.

Although several symmetrical displacement-length profiles have been interpreted from field data, primarily from normal faults (e.g., Muraoka and Kamata, 1983; Walsh and Watterson, 1987; Krantz, 1988; Opheim and Gudmundsson, 1989;
Peacock and Sanderson, 1991; Dawers et al., 1993; Dawers and Anders, 1995), such profiles are based on two assumptions that may not always be valid. First, a fault surface has been assumed to have the maximum displacement at or near the outcrop surface (Barnett et al., 1987), thereby implying that the trace of an active fault corresponds to the maximum dimension of the fault surface (Nicol et al., 1996). Second, fault surfaces are assumed to have a regular elliptical shape at depth, as well as elliptical displacement contours concentric about a centrally located maximum displacement (Nicol et al., 1996). However, Nicol et al. (1996) have shown that the maximum displacements on normal faults may not always be at the initial free surface. Furthermore, displacement contour diagrams from seismic reflection data and coal-mine plans show that normal fault surfaces tend to have irregular shapes and nonelliptical displacement contours (Nicol et al., 1996). Therefore, symmetrical displacement-length profiles appear to be dependent on the assumption that fault surfaces have an uniform shape and displacement distribution, which may not be the case in real-world situations. Complicating this debate is the inclusion of strike-slip, reverse, or oblique-slip fault data with data from normal faults. Such inclusion tends to produce displacement-length profiles that deviate from the symmetrical profiles predicted by the process zone model (Nicol et al., 1996).

The displacement-length profile analysis associated with the process zone model is affected by the nonuniform nature of faults to such a degree that it cannot be generally applied to fault-growth modeling. Slip along a fault surface can vary as a result of lithologic variations (Bürgmann et al., 1994), interaction with other faults (Willemse et al., 1996), irregular fault geometries (Schultz and Aydin, 1990), and processes such as pressure solution (Willemse et al., 1997). Furthermore, many slip distributions along faults with accumulated slip (Walsh and Watterson, 1987), as well as slip data from single earthquake events (Rymer, 1988), reveal that the slip is
distributed nonelliptically along fault surfaces (Cooke, 1997). Thus the nonuniform nature of slip along fault surfaces impacts the statistical analysis of displacement-length data. Combined with the problem of scale and the effects of different faulting regimes, the use of displacement-length profile analysis to explain and predict fault growth through time requires revaluation to reflect the nonuniformity associated with fault systems and tectonic environments.

The fracture linkage model also fails to explain many of the characteristics present within the fault zones investigated for this study. The discrepancy between my field observations and the predictions of the fracture linkage model poses an interesting paradox because the basic tenets of the fracture linkage model were developed from field observations within the same study area as my investigation. Thus not only is it necessary to describe the differences between my field observations and those predicted by this model, but it is also necessary to explain how such differences can exist within the same area.

A key characteristic of the fracture zone model is that a rotation of the stress field is required to activate preexisting joints as strike-slip faults. The first stress orientation forms the joints, some of which become strike-slip faults after a rotation of the stress field occurs that favors Mode II or III displacement (Segall and Pollard, 1983b). The strike-slip faults do not propagate in-plane, but link together by way of tensile fractures to form longer, continuous fault traces (Martel et al., 1988). Thus rotation of the stress field is important to the fracture linkage model in explaining the formation of splay fractures, horsetail splays, and stepovers. The fault zones that I investigated do not indicate that multiple stress orientations have occurred through time. While splay fractures, horsetail splays, and stepovers are present, they are a minor element in the overall geometry of the fault zones. Instead, long fracture and fault traces commonly interact by simply joining together at a junction, a geometry
not predicted by the fracture linkage model. Furthermore, evidence for the existence of preexisting joints is not present within the fault zones, suggesting that every preexisting joint was reactivated as a strike-slip fault, or that such joints never initially formed. The former explanation is unreasonable in light of previous investigations within the Lake Edison Granodiorite (e.g., Segall and Pollard, 1983a, 1983b; Martel et al., 1988; Martel, 1990; Evans et al., 1996; Martel and Evans, 1996; Lim, 1998), whereas the possibility of the latter explanation is discussed below. This is not to say that a rotation, or rotations, of the stress field did not occur within the study area, just that the predicted results of such a rotation are not present within the fault zones that I investigated. As a result, another explanation besides a rotation of the stress field is necessary to explain the differences between my field data and the observations of other investigations in my study area.

There are three possible explanations for the discrepancies between my field observations and the predictions of the fracture linkage model. The first explanation is that the characteristics and geometries of faults and fault zones are a function of preexisting discontinuities. The fracture linkage model suggests that the preexisting joints within the Lake Edison Granodiorite nucleated as cooling fractures (Segall and Pollard, 1983a, 1983b). Once an external stress field was applied to the pluton, those faults which formed on the preexisting joints are not new faults, but reactivated discontinuities within the rock. In contrast, the fractures and faults within the fault zones investigated for this study may have nucleated as new discontinuities in the rock as a result of the same stress field. Preexisting discontinuities may respond differently to the same stress field than new discontinuities that formed at the same time, thereby producing different fault and fault zone characteristics and geometries within the same pluton.

A second explanation is that the characteristics and geometries of faults and
fault zones are a function of how stress is distributed within the pluton. Fault zones containing preexisting joints that later were reactivated as faults with shear displacement are located throughout the Lake Edison Granodiorite. But interspersed within the Lake Edison Granodiorite are areas in which preexisting joints, as well as faults and fault zones, are absent (Lockwood and Lydon, 1975, Fig. 2). If the pluton does not respond uniformly to an applied stress field, then different areas of the pluton will have fault and fault zone geometries representative of how the stress field was distributed within that area. As a result, the fracture geometry predicted by the fracture linkage model might develop in areas with a stress magnitude and orientation that is different from those in the three study sites investigated here. Thus different areas within the same pluton will have different fault and fault zone characteristics and geometries. In addition, the stress distribution within some areas of the same pluton may even be capable of resisting the formation of fractures all together, thereby explaining why fault zones are absent from some areas of the Lake Edison Granodiorite. This explanation suggests that the Lake Edison Granodiorite did not respond uniformly to an applied stress field. The third explanation is the possibility that both the first and second explanations occur, implying that the characteristics and geometries of faults and fault zones are a function of preexisting fractures and the nonuniform distribution of stress within the pluton.

Regardless which explanation is correct, the suggestion that a rock body does not respond uniformly to an applied stress field implies that stress orientation and magnitudes are not homogeneous within the rock body. This idea was not considered by the proponents of the fracture linkage model, thereby explaining why the predictions of the fracture linkage model do not match my field observations. Thus the nucleation and growth of faults and fault zones through time may be more dependent on nonuniform processes than previously realized.
As with the process zone and fracture linkage models, I have assumed that stress is the driving force behind the formation and growth of faults and fault zones. Although such an assumption is common, it is not necessarily appropriate in all situations (Twiss and Moores, 1992; Tikoff and Wojtal, 1998). The evolution of faults and fault zones may not be dependent primarily on the stress field, but a function of the imposed deformation occurring as these structures form. Such a suggestion is borne out by the shear model experiments of Schreurs (1994) and An and Sammis (1996).

The experimental investigations by Schreurs (1994) and An and Sammis (1996) eliminated preexisting joints, fractures, and faults. The magnitude and orientation of the applied stress was constant throughout the experiments. In contrast, the magnitude of strain increased as the experiments progressed. The resulting fault and fault zone geometries match extremely well with the geometries of the fault zones investigated for this study. Schreurs’s (1994) experiments produced long unsegmented fault traces, junctions between fault traces with characteristics similar to those in my study area, and transfer fractures. In addition, the results in Schreurs (1994) can explain the formation of the few curved traces present within the BCFZ (rotation along a vertical axis as a result of an increase in localized strain [Schreurs, 1994]). The formation and characteristics of steps and stepovers documented in the An and Sammis (1996) experiments match more closely to my field observations than those predicted by the fracture linkage model. Furthermore, a rotation of the overall stress orientation was not required to produce these structures. Thus the fault zone geometries produced by the shear model experiments match my field observations more closely than either the process zone or fracture linkage models.

The shear model experiments, combined with the field data obtained in this
study, suggest that the overall geometry of a fault zone is more dependent on the deformation occurring within the fault zone through time than the overall applied stress field. The growth of a fault can be modified by interaction either with a contemporaneous fault, or with a preexisting fault (Gillespie et al., 1992). An and Sammis (1996) noted that the nucleation, propagation, and orientation of fault traces are a function of the strain occurring within a fault zone. Schreurs (1994) documented that the first-generation master faults determined the orientation of subsequent faults. Secondary faults do not appear until after the parallel to subparallel master faults with considerable overlap have developed, suggesting that secondary faults form in response to modifications in the local stress field caused by previously formed master faults (Schreurs, 1994). When two faults grow laterally towards one another, they interact before intersecting because of the interference between their respective elastic strain fields which extend beyond the tip points (Nicol et al., 1996). This interaction weakens the unfractured rock between them, thereby promoting fault growth towards one another, not away from each other as predicted by the fracture linkage model (Segall and Pollard, 1987; Martel and Pollard, 1989). Such a mechanism might explain how the long fault traces documented in this investigation interact in-plane, and why fault traces branch away from junctions with relatively consistent strikes along trace. Therefore, it appears that as the strain within a fault zone changes, the geometry of the fault traces comprising the fault zone also changes, further altering the deformation within the fault zone and promoting the formation of new structural features through time.

Whereas the nucleation of faults appears to be dependent on the applied stress, the propagation of the faults may be dependent on the strain occurring through time. The question is which process, stress or strain, is the boundary condition constraining fault and fault zone development? Or is it possible that the boundary
conditions change with fault or fault zone evolution? Consider the possibility that
a fault initially nucleates in response to some applied stress field. At some point,
perhaps after some direct or indirect interaction with another fault, the strain resulting
from such interaction becomes the driving force behind the further propagation of the
fault. Such a suggestion does not require a change in the stress orientation or
magnitude, that the stress is applied uniformly throughout the rock body, that slip is
distributed uniformly along the fault, or that the lithology be homogeneous.

Once a through-going shear fault zone develops, deformation within the fault
zone becomes nonuniform and strain is predominantly accommodated by the
through-going shear fault zone (An and Sammis, 1996). Such a through-going shear
fault zone may be manifested by the simple fault zones documented by this
investigation and the investigations of Martel et al. (1988), Martel (1990), and Martel
and Evans (1996). Thus the boundary conditions governing the development of
faults or fault zones may be stress, strain, or a combination of both.

The field data obtained in this investigation suggest that faults and fault zones
nucleate and grow in a nonuniform manner. The variations in rock types and tectonic
environments, style of faulting, the existence of preexisting structures, interactions
between fractures or faults, and the effects of non-faulting processes, such as
hydrologic flow, indicate that fault growth is an evolving, nonuniform process.
Furthermore, the effects of deformation on the propagation of faults and fault zones
imply that strain may be the boundary condition for the growth of these structures.

Although several smaller-scale features are not addressed by the shear model
experiments, this fault-growth model comes the closest in describing the overall
nucleation and propagation of the fault zones that I investigated. The fracture linkage
model can explain many of the smaller-scale features, but not the development of the
fault zones. Thus this fault-growth model is more applicable for explaining the
development of specific structures, like the two simple fault zones within the BCFZ. Finally, the process zone model is least able to explain the characteristics and geometries documented in this study and cannot be used to describe the fault growth of the fault zones that I investigated.

None of the three fault-growth models discussed here completely explain the characteristics and geometry of the fault zones investigated for this study. Thus it might be necessary to consider the possibility that no single fault-growth model can explain all cases of fault nucleation and propagation, as well as the development of fault zones. Although a general fault-growth model may be possible, such a model will need to be flexible enough to incorporate the variations associated with specific faulting environments and faulting regimes.

Regardless of whether an all-encompassing fault-growth model or multiple fault-growth models are developed, such models will still be an idealization of real-world conditions. While such idealized models are a useful first step in understanding and representing the growth of faults and fault zones, rigorous fault-growth models will need to incorporate the effects of nonuniformity occurring throughout the faulting process. Furthermore, revaluation of the boundary conditions to incorporate strain may be necessary for future fault-growth models. Although the inclusion of nonuniform variables and using strain as a boundary condition may substantially complicate fault-growth models, the resulting models will more accurately represent real-world conditions. To facilitate the development of rigorous fault-growth models, the use of three-dimensional representations, based on theoretical analysis and constrained by field investigations, are imperative. These three-dimensional representations will provide an important foundation for developing credible models describing the nucleation and growth of faults and fault zones.
CONCLUSION

The field data obtained for this study suggest that concepts and processes not incorporated in current fault-growth models, as well as three-dimensional sampling, need to be considered in order to create more realistic fault-growth models. The geometry and distribution of the fracture and fault traces documented in this study are similar to those produced in experiments in which strain, or deformation, was the primary boundary condition. My field data support the suggestion of the shear model experiments that the growth of fractures and faults affects the nucleation, propagation, and geometry of subsequent fractures and faults. I interpret the data to show that continued nonuniform deformation within a fault zone eventually resulted in the formation of a through-going shear zone, similar to the two simple fault zones present within the BCFZ. Further strain would be primarily accommodated within the simple fault zone, thereby concentrating future deformation and growth to such through-going structures.

The differences in fault zone geometry between those fault zones that I investigated and those investigated in the same area by Segall and Pollard (1983b), Martel et al. (1988), and Martel (1990) may be a reflection of the nonuniform response of an otherwise homogeneous rock body to stress. Those areas containing preexisting discontinuities have different fault zone geometries than those areas that lacked preexisting fractures before the stress field was applied. This difference in fault zone geometries suggest that the nonuniform distribution of pre-existing fractures within a homogeneous rock body affects future fault zone development. Furthermore, the differences in fault zone geometries also indicate that stress orientation and magnitude may not be uniform throughout the rock body. This idea might explain how different fault zone geometries form in the same rock body, as
well as why some areas within the rock body lack fault zones altogether.

The distribution of slip, along an individual fault trace or the trace of a fault zone, is irregular at all scales of observation. This has serious implications for the statistical analysis of displacement-length profiles that assume a regular slip distribution in order to describe fault-growth histories. Thus the displacement-length profiles created from data obtained in this study support the suggestion that fault and fault zone development is an irregular process, and that the deformation occurring through time controls the nucleation and growth of subsequent features.

Although the shear model experiments come very close in describing the overall nucleation and propagation of the fault zones investigated for this study, none of the three fault-growth models discussed in this study (the fracture linkage model, the process zone model, and the shear model experiments) can completely explain all the characteristics and geometries of the faults and fault zones. Only the process zone model can be completely dismissed. It is possible that no single fault-growth model can explain fault and fault zone nucleation and propagation. Future fault-growth models, whether generalized or specific to a particular faulting regime or environment, should incorporate the variability and complexity associated with the nonuniform nature of fault and fault zone development. Furthermore, the variability of the boundary conditions, whether it is stress, strain, or both, will need to be included in any comprehensive fault-growth model. To facilitate such rigorous fault-growth modeling, the use of three-dimensional representations of the faults and fault zones will be a powerful tool.

Current computer-generated three-dimensional depictions of faults and fault zones are based on field studies of individual fault traces. Although constrained by actual geologic information, these three-dimensional visualizations assume idealized fault surfaces and regular geometries. Such visualizations are an excellent first step
in depicting the three-dimensional structure of faults and for modeling faulting processes. However, my field data suggest that faults and fault zones are complex, interacting structures with substantial variations in terms of slip distribution, linkage structures, and overall geometries. This variability, combined with nonuniform mechanical faulting processes, will need to be incorporated into any future three-dimensional representation in order to develop accurate fault-growth models.

Perhaps fault-growth modeling should initially concentrate on explaining fault growth based on idealized three-dimensional visualizations and uniform mechanical processes. Once a basic understanding of fault and fault zone nucleation and growth is obtained, the inclusion of more complex structural features and nonuniform variables can be added to the basic model. In time, a fault-growth model, or models, representative of real-world conditions may emerge.
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