# Chapter 1

## Structure and history of the Kern Canyon fault system: introduction and thesis overview

Exposures of fault zones from the surface to deep levels afford an opportunity to study the transition of rock behavior from brittle to ductile conditions. In the Sierra Nevada batholith, one of the best studied magmatic arcs in the world, ~5 km to ~30 km of exhumation in the southern end of the batholith exposed rocks that formed and were deformed in shallow to deep crustal settings. During Cretaceous time, in the waning stages of arc magmatism, several faults arose in the batholith in response to changing plate kinematic forces at the adjacent Farallon–North American plate boundary. Ductile fabrics of these faults record a change from compression to transpression across the active magmatic arc. When magmatism ceased, deformation continued in the brittle regime in the batholith as it slowly cooled. Regional detailed mapping and microstructural studies provide the framework with which to clarify the degree of strain within the arc. Geochronological and geobarometric studies provide the temporal and physical links for the transition in faulting from early thrusting to subsequent dextral shear, and from early ductile to subsequent brittle deformation in the southern Sierra Nevada.

At ~150 km long, the Kern Canyon fault of the southern Sierra Nevada is the longest through-going fault in the batholith. It is clearly expressed geomorphically as a north–south trending scar beside which the Kern River flows through the mountainous topography. The Kern Canyon fault was first described in detail in a 1936 PhD thesis by

Caltech student Robert Webb, who traced it for a length of ~40 miles from the town of Kernville to Golden Trout Creek at the southern end of the Sequoia National Forest. In 1978, the first attempt to estimate offset along the Kern Canyon fault, by James Moore and Edward du Bray, also proposed an age for initiation of brittle faulting. Individual plutons as young as 80 Ma within the southern part of the batholith were interpreted to be cut and offset in a dextral strike-slip sense by the fault, by ~6 km in its upper reaches and up to ~13 km at its southern end. In 1986, Donald Ross suggested that at its southern end the Kern Canyon fault joined with the active Breckenridge and White Wolf faults sequentially, eventually exiting the Sierra to the southwest.

In 1990, Cathy Busby-Spera and Jason Saleeby found extensive evidence for ductile deformation along a broad zone around the Kern Canyon fault, and called it the Proto-Kern Canyon fault. This name suggested, at the very least, that the Proto-Kern Canyon fault formed a weak zone along which the later Kern Canyon fault localized, and at the most it suggested that these two faults were the deeper-level ductile and shallower-level brittle expression of the same fault system. Indeed, both faults appeared to have undergone dextral strike-slip motion. Proto-Kern Canyon fault motion was placed between 100 and 83 Ma based on zircon U/Pb ages of ductilely deformed plutons within the fault zone. Soon after, several other ductile faults were reported from the central–southern part of the batholith. They all seemed to share a similar deformation sense and timing: early ductile thrusting followed by dextral strike-slip shear that lasted until ca. 80 Ma. Those that fell along a continuous line were suggested to constitute a 250 km long shear zone dubbed the Sierra Crest shear zone system by Basil Tikoff (1994).

Recently, a deformation and exhumation chronology was established for the southernmost part of the batholith (see Saleeby et al., 2007). In this region, ductile deformation fabrics along an ~5 km wide zone appear to be the southern continuation of the Proto-Kern Canyon fault. These fabrics strike north–south and their dips shallow progressively southward, until the ductile fabrics merge with other high-strain rocks near the Garlock fault. The southernmost part of the batholith likely underwent significant east-side-up vertical thrusting in mid- to Late Cretaceous time. The continuity of shallow-dipping, ductilely deformed rocks in the southernmost Sierra with those of the generally steeper-dipping Proto-Kern Canyon fault to the north suggest that in its early stages, the Proto-Kern Canyon fault was a ductile thrust zone. The chronology established by Busby-Spera and Saleeby suggests that it transitioned into a dextral-slip fault by 90 Ma. Strike-slip motion continued in the ductile regime along much of the Proto-Kern Canyon fault until ca. 80 Ma, at which time this region cooled through 300˚ C and brittle fractures and joints formed (e.g., Segall, 1990). This age corresponds to the timing of brittle offset along the Kern Canyon fault suggested by Moore and du Bray (1978). However, the southernmost part of the batholith had cooled through 300˚ C by ca. 85 Ma, suggesting that brittle faulting was established in the south earlier than it was in the north. This information poses the possibility that Kern Canyon fault displacement began in the south and progressed northward, merging with the Proto-Kern Canyon fault as it was being exhumed progressively northward. If this is the case, then the cooling history of the batholith further suggests that the Kern Canyon fault was established west of the Proto-Kern Canyon fault in the southernmost part of the batholith, and that it joined the Proto-

Kern Canyon fault at the center of its length, from where it followed the trace of the Proto-Kern Canyon fault northward.

The timing and geometric relations of the Proto-Kern and Kern Canyon faults pose difficulties in interpreting the slip histories of each. The plutons used by Moore and du Bray (1978) to estimate offset in the northern part of the Kern Canyon fault are elongate and were likely stretched during emplacement along the ductilely deforming Proto-Kern Canyon fault. Displacement estimates for the Proto-Kern Canyon fault suggest that 4–6 km of vertical thrusting were followed by 5–15 km of dextral strike-slip shearing. Refinement of pluton boundaries and pluton emplacement ages reported in Chapter 2 of this thesis suggest that the most reliable brittlely offset pluton boundaries lie west of the Proto-Kern Canyon fault, along the Kern Canyon fault south of where the two structures merge. These plutons are not elongate, nor are they ductilely deformed. Finally, recent field studies show that brittle faulting continued along the Kern Canyon fault through Quaternary time, with east-side-up normal motion. These topics will be summarized briefly below, and presented in detail in this thesis.

**Thesis overview**

The study area of this thesis (plate 1) covers the southern Sierra Nevada batholith along longitude 118.5˚ W from the Garlock fault in the south (latitude ~35˚ N) northward to latitude 36.5˚ N. The thesis work entailed 1) detailed fieldwork consisting of geologic mapping, structural analyses, field petrology, and sample collection; 2) petrographic and microstructural analyses; 3) sample preparation for and interpretation of zircon U/Pb analyses; 4) electron microprobe measurements of the Al content of hornblende to determine emplacement pressures of plutons; and 5) building and interpreting large GIS-based contour maps of published and new geochemical data. Below I present an overview of the main chapters of my thesis, which together constitute a ca. 95 Myr history of deformation for a ~150 km long, intra-arc fault zone.

**Chapter 2** is modified from a paper published in a 2007 GSA volume dedicated to geologist Cliff Hopson. I am a coauthor on the paper, which presents new zircon U/Pb ages for plutons of the southern Sierra Nevada in the vicinity of the Proto-Kern Canyon fault. The new ages, combined with field mapping and petrographic analyses, refine the chronology of emplacement of suites of plutons in the area, establishes one new suite, and refines the timing of ductile deformation along the Proto-Kern Canyon fault. My contribution to the paper consisted of sample collection, mapping, petrographic analyses, and data interpretation. I omitted a section describing pluton emplacement mechanisms and a section detailing the history of a sub-volcanic complex in the map area. The geochronology presented in this chapter is crucial to interpreting the timing of deformation along the Proto-Kern Canyon fault.

**Chapter 3** presents a detailed analysis of large geochemical and geobarometric data sets for the southern half of the Sierra Nevada batholith, and is published in the same GSA volume as Chapter 2. These data provide insights into the earliest history of the Proto-Kern Canyon fault. Differences in pluton emplacement depths across the fault suggest that this early history entailed east-side-up vertical motion of ~4–6 km. The truncations of a regional geochemical tracer, the $Sr_i$ = 0.706 line, and of a principal zone of the batholith (defined chemically and chronologically) along the Proto-Kern Canyon fault provide constraints on how much crustal shortening took place during the early history of the shear zone.

In **Chapter 4**, a detailed microstructural analysis is undertaken to establish the degree of ductile deformation across the northern half of the Proto-Kern Canyon fault. Steeply and shallowly plunging mineral stretching lineations support the idea presented in Chapter 3 that the shear zone accommodated both vertical and strike-slip offset. Strain analyses of mylonitic granite and mylonitic pendant rocks in this study area provide a minimum dextral offset along the shear zone, and, when combined with the duration of dextral shearing, suggest a strain rate with the same order of magnitude as that of modern-day strike-slip fault zones. Interpretation of deformation regimes of quartz aggregates suggests that the shear zone was localized along the contact between one pluton that was emplacing and deforming during shearing along the fault, and several other plutons that had intruded ca. 5 m.y. prior to initiation of ductile shearing.

**Chapter 5** presents displacement estimates from strain analyses in two other locations along the central region of the Proto-Kern Canyon fault. These calculations match those presented in Chapter 4. A larger displacement is suggested by the aspect ratios of igneous and metamorphic pendant bodies stretched and deformed along the fault. In addition, an estimate of paleostress along the fault is presented, based on the recrystallized quartz grain piezometer introduced by Twiss (1977). Stress estimates are combined with reasonable estimates for temperatures during deformation to yield a strain rate for this segment of the Proto-Kern Canyon fault.

Finally, **Chapter 6** presents a detailed history of brittle faulting along the Kern Canyon fault. Reconnaissance studies from both the ground and the air revealed several fresh-looking fault scarps that indicate brittle faulting continued through Quaternary time. These scarps show west-side-up normal offset, suggesting Cretaceous dextral strike-slip motion gave way to normal faulting in Neogene time. Continued seismicity in the area is sometimes located on the Kern Canyon fault, but more often takes place ~10 km east of the fault, posing the possibility that the locus of low-magnitude deformation is progressing eastward. This observation is used to speculatively assign forces responsible for recent deformation within the Sierra Nevada batholith to convective removal of the mantle lithosphere.