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The Gem Lake shear zone: Cretaceous dextral transpression in the Northern Ritter Range pendant, eastern Sierra Nevada, California

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Abstract. The Gem Lake shear zone is a northwest striking, steeply dipping, dextral transpressional shear zone that provides the first direct evidence for dextral deformation in wall-rock pendants in the central part of the Sierra Nevada batholith. The Gem Lake shear zone is a minimum of 30 km in length and extends at least from the north end of the Northern Ritter Range pendant to the southeast edge of the Ritter Range pendant. The amount of displacement on the zone is uncertain, but matching fault slivers of Pennsylvanian(?) marble in the Northern Ritter Range pendant to similar exposures north of the Mount Morrison pendant suggests a minimum dextral offset of 20 km. The Gem Lake shear zone was active in early Late Cretaceous time, from before 91 Ma (the age of the syntectonic granodiorite of Kuna Crest) to at least 80 Ma ($^{40}Ar/^{39}Ar$ age of syndeformational mica from the shear zone in the Ritter Range pendant). Deformation in the Gem Lake shear zone is characterized by combined dextral simple shear and subvertical stretching, which are variably partitioned in anastomosing high-strain zones. In the shear zone at Gem Lake, predominantly dextral deformation is indicated by porphyroclast asymmetries, S-C fabric, and asymmetric crenulations; a component of subvertical stretching is indicated by a moderately to steeply plunging stretching lineation. In a segment of the shear zone at Kuna Crest, a strongly developed stretching lineation indicates predominantly subvertical stretching, with a lesser component of dextral strike slip. The Gem Lake shear zone is considered to be part of a proposed regional system of shear zones in the eastern Sierra Nevada, the Sierra Crest shear zone system. This dextral transpressional system was active prior to, and synchronous with, intrusion of the Late Cretaceous Sierra Nevada batholith; deformation ceased shortly after pluton emplacement. The Sierra Crest shear zone system includes possibly related shear zones as far north as Saddlebag Lake pendant and at least as far south as Oak Creek pendant and the Owens Valley, indicating a possible strike length greater than 150 km.

Introduction

In this paper we describe evidence for, and the components of, the Gem Lake shear zone, a northwest striking, dextral transpressional shear zone exposed in the Northern Ritter Range pendant in the east-central Sierra Nevada (Figure 1). Late Mesozoic dextral strike-slip faults have previously been proposed in the central and eastern Sierra Nevada by a number of workers [e.g., *Nokleberg*, 1983; *Saleeby et al.*, 1986; *Lahren et al.*, 1990; *Tikoff and Teyssier*, 1992; *Stevens et al.*, 1992; *Kistler*, 1993]. However, the location, extent, and regional tectonic significance of these faults have been controversial [e.g., *Schweickert and Lahren*, 1991; *Saleeby and Busby*, 1993] and remain an important unresolved question. The Gem Lake shear zone provides the first direct field evidence for a dextral shear zone in the wall-rock pendants of the central Sierra Nevada and along with other proposed faults suggests that middle Cretaceous deformation in the Sierra Nevada may have been characterized by distributed dextral transpression on anastomosing, northwest trending shear zones of regional extent.

In this paper we first describe the Gem Lake shear zone in the Northern Ritter Range pendant, with emphasis on its field expression, structural style, and deformational history. We then discuss possible regional continuations of the Gem Lake shear zone and the tectonic implications of a dextral transpressional shear zone system in the eastern Sierra Nevada. In this paper we emphasize evidence for dextral transpression in the wall-rock pendants of the Sierra Nevada batholith. *Tikoff and Teyssier* [1992, 1993a] and *Tikoff and Greene* [1994] have described evidence for similar dextral transpression in the Late Cretaceous granitoids of the batholith itself. We consider that transpressional deformation in the wall rocks and the batholith are related and suggest that the Gem Lake shear zone is part of a proposed Sierra Crest shear zone system [*Tikoff*, 1994; *Tikoff and Greene*, 1994], defined as an anastomosing system of dextral shear zones exposed locally throughout the eastern Sierra Nevada (Figure 1).

Geologic Setting

The Northern Ritter Range pendant (NRP) is located in the east-central Sierra Nevada, at the eastern edge of Yosemite National Park. The NRP is one of a number of roof pendants and wall-rock septa preserved within Mesozoic granitic rocks of the Sierra Nevada batholith. It consists of a narrow septum of Paleozoic metasedimentary rocks and Mesozoic metavolcanic rocks that extends 20 km northwest from the larger Ritter Range pendant [*Kistler*, 1966a, b; *Huber and Rinehart*, 1965]. Strata in the NRP generally strike northwest, dip steeply to the southwest, and are younger to the southwest.

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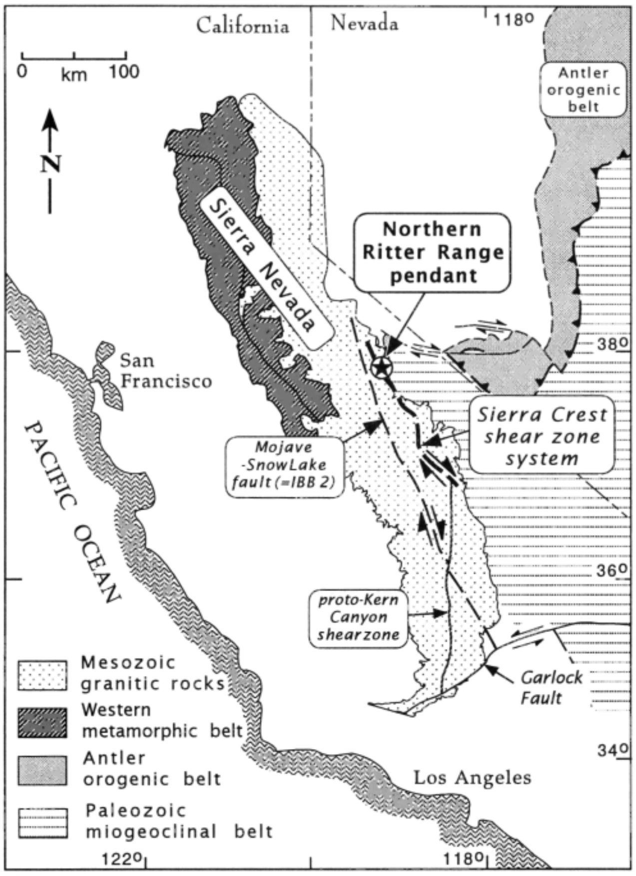

Figure 1. Generalized regional map showing the location of the Northern Ritter Range pendant in relation to the Sierra Nevada and the proposed Sierra Crest shear zone system. Modified from *Jennings* [1977], with data from *Schweickert and Lahren* [1990] and *Saleeby and Busby* [1993].

A geologic map of the NRP (Figure 2) thus represents an oblique cross section through the pendant. All pre-Tertiary rocks in the NRP have been metamorphosed under greenschist to epidote amphibolite facies conditions; however, the prefix meta- has been omitted in subsequent descriptions where the protolith is readily discernible.

Stratigraphy of the NRP

The structurally lowest unit in the NRP is the lower Paleozoic Rush Creek sequence [*Strobel,* 1986; *Greene,* 1995], which consists of siliceous and calc-silicate hornfels, chert, marble, and quartzite. The Rush Creek sequence is interpreted as a transitional facies of the Paleozoic Cordilleran miogeocline [*Strobel,* 1986; *Greene et al.,* 1989; *Greene,* 1995].

The structurally overlying Palmetto Formation consists predominantly of highly disrupted and deformed chert and siliceous argillite, with local calc-silicate hornfels and quartz siltstone. This unit, together with exposures to the north in the Saddlebag Lake pendant, is considered to be correlative with the Ordovician Palmetto Formation of the Roberts Mountains allochthon [*Schweickert and Lahren,* 1987; *Greene et al.,* 1989; *Greene,* 1995].

Small structural slices of fossiliferous marble of late Paleozoic (Pennsylvanian?) age [*Brook et al.*, 1979; *Greene and Dutro,* 1991; *Greene,* 1995] are interleaved with the Palmetto Formation northwest of Alger Lakes (Figure 2). These fault slices are correlative with the Pennsylvanian Mount Baldwin Marble, which is exposed in the Mount Morrison pendant 30 km to the southeast [*Greene and Dutro,* 1991].

The Paleozoic metasedimentary units are structurally and unconformably overlain to the southwest by the Upper Triassic to Lower Jurassic Koip sequence [*Huber and Rinehart,* 1965; *Kistler,* 1966a, b; *Schweickert and Lahren,* 1987, 1993b]. The Koip sequence is a varied assemblage of volcanic and subordinate volcanogenic sedimentary rocks. It consists predominantly of lapilli tuffs and tuff breccias and includes volcanic flows, hypabyssal intrusions, and lenses of volcanogenic sandstone. Composition of the volcanic rocks ranges from basalt to rhyolite but is predominantly dacitic to rhyodacitic [*Huber and Rinehart,* 1965]. The base of the Koip sequence in the Saddlebag Lake pendant has been dated at 222 Ma (U/Pb [*Schweickert and Lahren,* 1987]), and an ash-flow tuff from the top of the sequence has yielded a U/Pb age of 201 Ma [*Schweickert et al.,* 1994].

The Koip sequence is overlain by a Lower Jurassic volcanosedimentary unit informally referred to as the Sawmill Canyon sequence for a well-exposed section in the Saddlebag Lake pendant [*Greene,* 1995]. The Sawmill Canyon sequence is exposed in a thin strip along the west edge of the NRP, where it is composed of thinly layered volcanogenic sandstones and calcsilicate rocks, now metamorphosed predominantly to biotite schist.

The NRP is bordered on the east by the Late Triassic granite of Lee Vining Canyon (210 Ma U/Pb) [*Chen and Moore,* 1982]. On the west the NRP is bordered by the Late Cretaceous granodiorite of Kuna Crest (91 Ma U/Pb) [*Stern et al.,* 1981], which is part of the outer zone of the Tuolumne Intrusive Suite [*Bateman,* 1992].

Structure of the NRP

Multiple generations of structures in the NRP record various contractional and transpressional regimes of middle Paleozoic to late Mesozoic age. Two generations of middle or late Paleozoic structures are recognized in the NRP [*Greene,* 1995]. These include (1) isoclinal folds and transposed bedding in the Palmetto Formation that are generally northwest trending as a result of reorientation by third-generation structures; and (2) northeast trending mesoscopic folds and map-scale nappe folds that are best developed in the Rush Creek sequence. One or both of these sets of structures probably formed during the Antler orogeny, and a southwestern extension of the Roberts Mountains thrust has been proposed to separate the Palmetto Formation and Rush Creek sequence in the NRP [*Greene et al.,* 1989; *Greene,* 1995].

A third generation of structures that formed in Jurassic or Early Cretaceous time is characterized by a northwest striking slaty cleavage, which is generally parallel to transposed bedding and axial-planar to tight mesoscopic folds. This northwest trending structural fabric is developed throughout the NRP and is associated with prominent thrust faults which

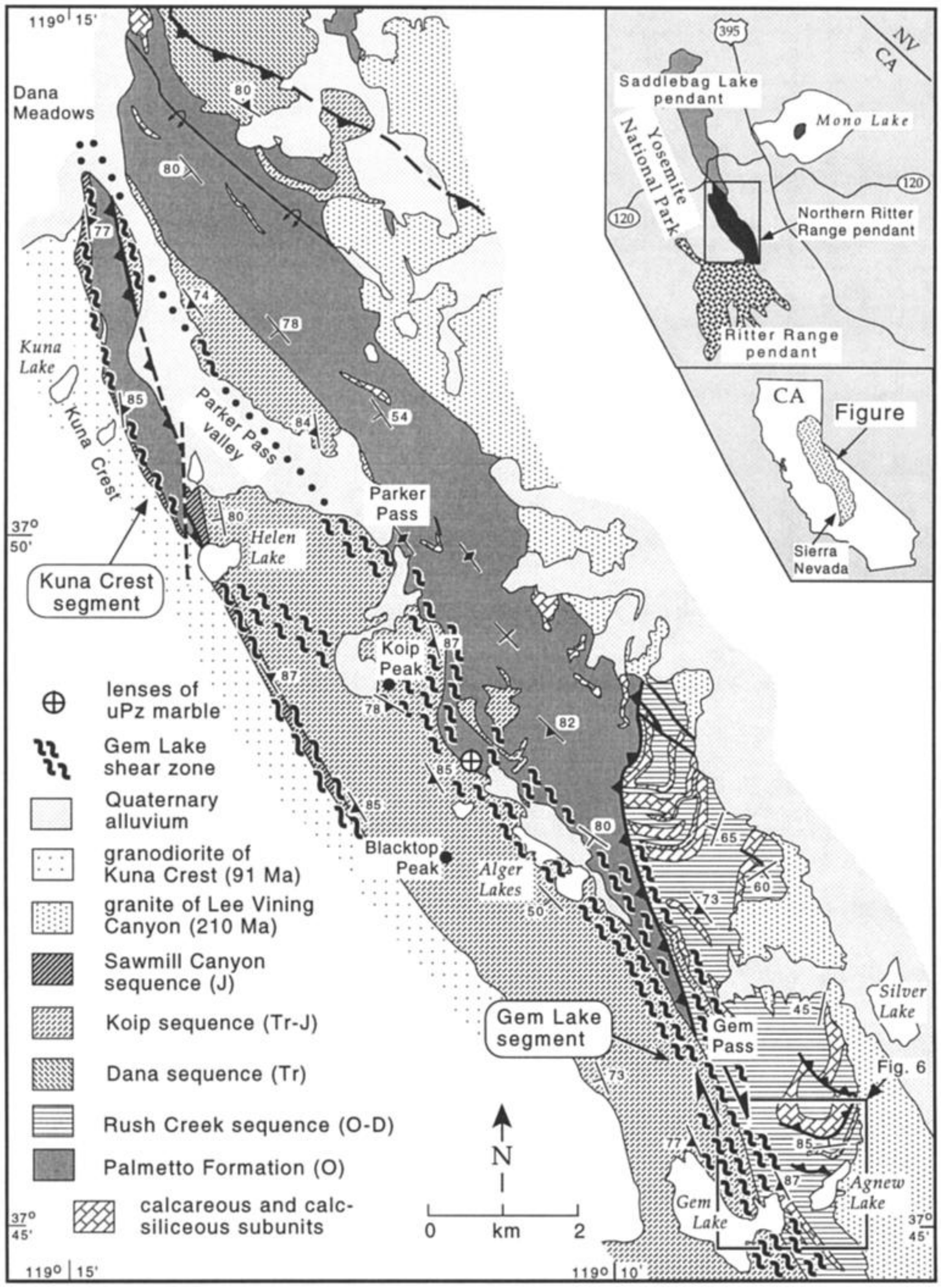

Figure 2. Generalized geologic map of the Northern Ritter Range pendant, showing the Gem Lake and Kuna Crest segments of the Gem Lake shear zone (modified from *Greene* [1995]).

imbricate Lower Jurassic rocks of the Koip and Sawmill Canyon sequences. These structures are cut by Late Cretaceous plutons [*Schweickert and Lahren*, 1987, 1993a, b] and indicate that a significant phase of Jurassic or Early Cretaceous contractional deformation affected the entire NRP.

There are no stretching lineations associated with regional deformation in the Paleozoic rocks. Moderate to poorly developed stretching lineation in Mesozoic rocks on the southeast side of the NRP is interpreted to result primarily from distributed deformation related to the Gem Lake shear zone.

Northwest trending structural fabric that is present in pendants throughout the central and southern Sierra Nevada [*Nokleberg and Kistler*, 1980; *Nokleberg*, 1983] was formerly interpreted to be predominantly Jurassic in age and related to the Nevadan orogeny [*Nokleberg and Kistler*, 1980;

Schweickert et al., 1984]. However, in some areas a northwest trending structural fabric is present in rocks of Early and middle Cretaceous age [*Tobisch et al.,* 1986; *Saleeby et al.,* 1990], suggesting that some of the northwest trending structural fabric in the NRP may be as young as Cretaceous.

Mylonitic foliation associated with the Gem Lake shear zone is subparallel to, and generally merges with, the northwest trending structural fabric. A prominent stretching lineation is present on foliation planes within the shear zone. Structural relations in the NRP suggest that Late Jurassic or Early Cretaceous regional contractional deformation, which resulted in thrust faulting and the third-generation contractional fabric, progressively evolved into dextral transpressional deformation in the middle Cretaceous, possibly with reactivation of the older contractional fabric.

Transpressional Deformation in the Gem Lake Shear Zone

The Gem Lake shear zone is a high-strain zone developed by a combination of dextral shearing and subvertical stretching associated with horizontal shortening. As described in detail below, horizontal exposures within the shear zone show dextral strike-slip shear indicators, including asymmetric porphyroclasts, S-C fabric, rotated veins, and asymmetric minor folds. In contrast, steeply dipping surfaces commonly show evidence of subvertical stretching, including symmetrically extended porphyroclasts and well-developed, steeply plunging stretching lineation.

A conceptual model for this style of deformation is illustrated in Figure 3. A ductilely deforming dextral shear zone is located between two unstrained blocks. Horizontal shortening perpendicular to the shear zone boundaries (indicated by full arrows) results in vertical stretching of the rocks within the shear zone and the development of a steeply plunging stretching lineation. Synchronous dextral simple shear parallel to the shear zone boundaries (indicated by half arrows) results in dextral displacement across the shear zone, as indicated by asymmetric porphyroclasts and other dextral strike-slip shear indicators. Note that in this model the stretching lineation tracks the direction of maximum finite stretching (x axis in Figure 3), not the displacement direction.

This combination of horizontal simple shear and subvertical extension is characteristic of transpressional shear zones in which the stretching direction is perpendicular to the shear direction [*Sanderson and Marchini,* 1984; *Simpson and De Paor,* 1993; *Robin and Cruden,* 1994]. Modeling studies [*Fossen and Tikoff,* 1993; *Fossen et al.,* 1994] have shown that with increasing finite strain in a transpressional shear zone, the stretching lineation will migrate to a subvertical orientation, reflecting the orientation of the maximum finite stretching axis. This result holds true even for transpressional shear zones in which the simple shear component of deformation (and the amount of strike-slip displacement) is large relative to the pure shear component [*Tikoff and Teyssier,* 1993b; *Fossen et al.,* 1994]. Transpressional shear zones with coexisting horizontal strike-slip shear indicators and vertical stretching lineation have also been described by *Robin and Cruden* [1994] in the Larder Lake Break in the Superior Province of Canada and by *Hudleston et al.* [1988] in the Vermilion District of northern Minnesota.

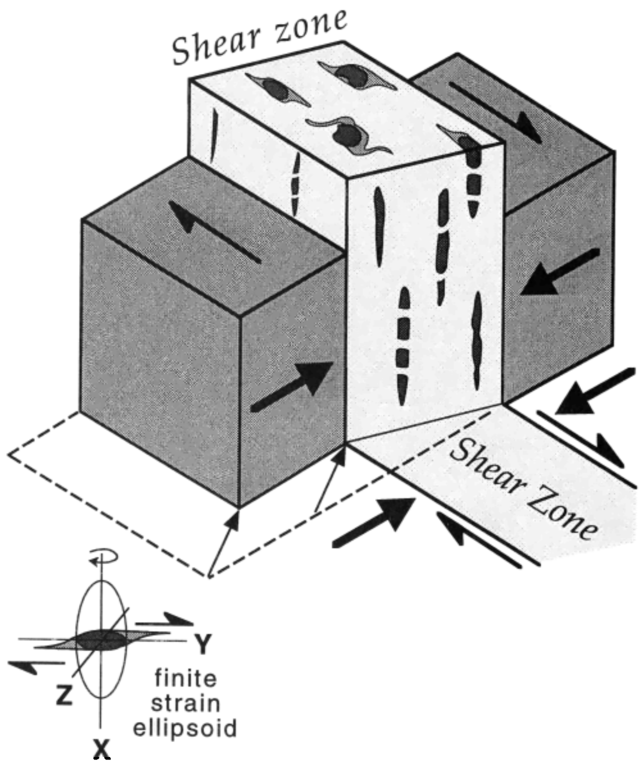

Figure 3. Model for dextral transpressional deformation in the Gem Lake shear zone. Full arrows indicate horizontal contraction, resulting in vertical extension within the shear zone and development of extension lineation visible on vertical surfaces. Half arrows indicate synchronous dextral shearing, resulting in dextral strike-slip displacement and development of dextral shear indicators visible on horizontal surfaces (after *Sanderson and Marchini* [1984]).

The Gem Lake Shear Zone in the Northern Ritter Range Pendant

The Gem Lake shear zone as defined in this paper consists of three segments: the Gem Lake segment, the Kuna Crest segment, and the Ritter Range segment (Figure 4). The simple shear and pure shear components of deformation are variably partitioned within and between these segments. The Gem Lake and Ritter Range segments are dominated by dextral simple shear with subordinate vertical stretching; the Kuna Crest segment exhibits dominant subvertical stretching with subordinate dextral simple shear. The following sections describe the Gem Lake and Kuna Crest segments separately and summarize evidence that these segments are components of the same shear zone. The Ritter Range segment is described in a later section.

Gem Lake Segment

The Gem Lake segment is the primary strand of the Gem Lake shear zone. It is a northwest striking, steeply southwest

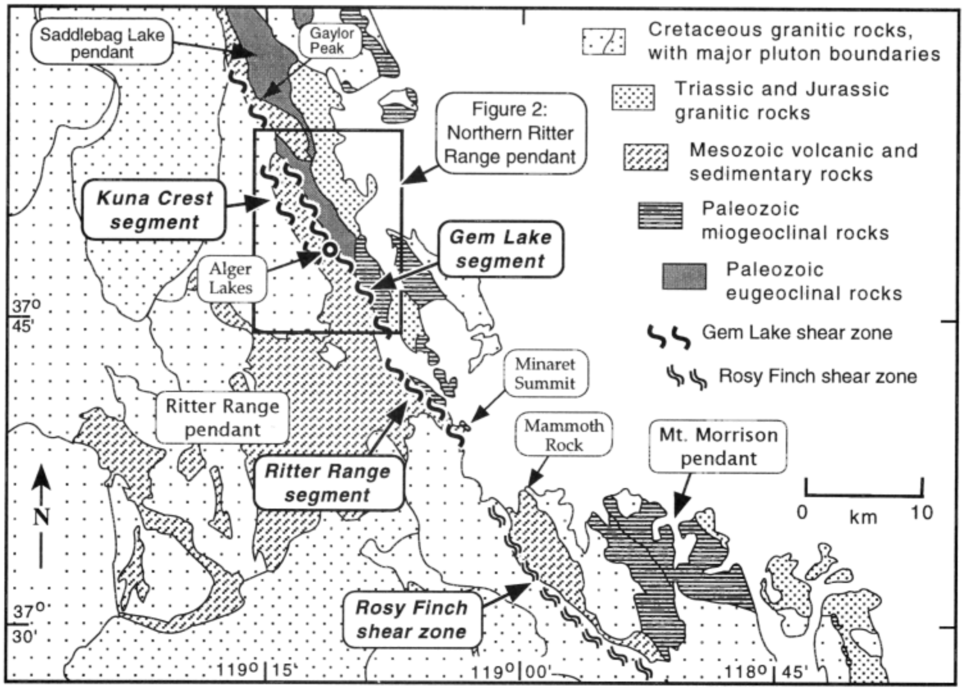

Figure 4. Generalized geologic map of part of the east-central Sierra Nevada, showing the Gem Lake, Kuna Crest, and Ritter Range segments of the Gem Lake shear zone (modified from *Bateman* [1992]).

dipping, high-strain zone that generally forms the contact between Paleozoic metasedimentary rocks and Mesozoic metavolcanic rocks. The Gem Lake segment extends the length of the NRP, from the north end of Parker Pass valley to the south end of the NRP, 2 km south of Gem Lake (Figure 2). This high-strain zone is especially well-developed in the vicinity of Gem Lake, where it was described by *Strobel* [1986].

The Gem Lake segment is characterized by anastomosing zones of mylonitic foliation striking N30-60W and dipping steeply to the southwest (Figure 5), generally parallel to northwest striking regional foliation. Foliation in the shear zone is distinguished from the regional foliation by its more intense development, including thinly spaced cleavage and concentrations of phyllosilicates on shear planes. In addition, foliation in the shear zone is associated with asymmetric porphyroclasts and other indicators of strike-slip deformation, and a prominent down dip extension lineation is present on foliation surfaces. Extension lineation is less well developed in metavolcanic rocks away from the shear zone and not present in metasedimentary rocks outside the shear zone. Locally well-developed slaty cleavage and aligned, flattened volcanic clasts indicate a significant component of flattening deformation parallel to mylonitic foliation. However, it has not been possible to distinguish flattening associated with middle Cretaceous transpression from that associated with previous regional deformation.

Mylonitic foliation is most prominent in volcanic and volcaniclastic rocks of the Koip sequence. The development of deformational features depends in part on lithology: highly cleaved mylonites occur in very fine-grained siliceous tuffs, S-C fabrics in fine- to medium-grained tuffs, asymmetric crenulation cleavage in phyllonites and phyllosilicate-rich schists, and asymmetric pressure shadows and winged porphyroclast systems in medium- to coarse-grained lapilli tuffs and tuff breccias. Quartz veins are commonly sheared and boudinaged, with asymmetric pressure shadows around individual boudins. All these features have asymmetries that indicate dextral strike-slip displacement. A significant component of vertical stretching is evidenced by a moderately

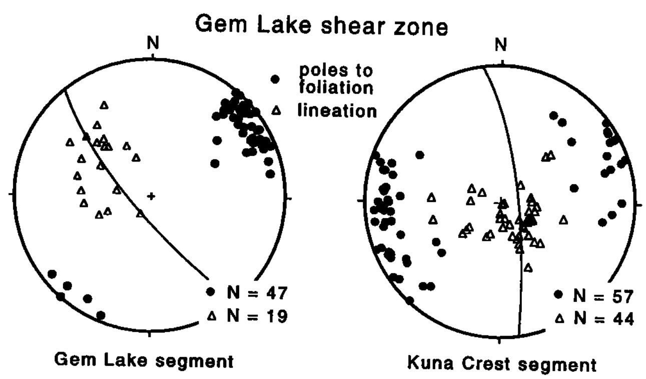

Figure 5. Equal area stereonets showing the orientations of foliation and lineation in the Gem Lake and Kuna Crest segments of the Gem Lake shear zone. The great circles represent average orientation of foliation: striking N40W and dipping 80°SW in the Gem Lake segment, striking N10W and dipping 80°NE in the Kuna Crest segment.

to steeply plunging stretching lineation which is visible on steeply dipping surfaces.

At Gem Lake, the shear zone consists of a kilometer-wide zone of highly strained metavolcanic and metasedimentary rocks. Particularly good exposures of the shear zone occur in lapilli tuffs of the Koip sequence along the northeastern shore of Gem Lake. To the east in the Rush Creek sequence, the shear zone is manifested by progressive breakup and overprinting of a preexisting northeast trending structural grain by northwest trending mylonitic foliation (Figure 6) [*Strobel*, 1986]. The shear zone continues 2 km southeast of Gem Lake to the southern end of the NRP, where it is overlapped by Tertiary basalt.

In the Palmetto Formation northwest of Gem Lake, the shear zone is characterized by anastomosing domains of mylonitic chert and siliceous argillite and by intense slaty cleavage developed in more argillaceous units. A network of orange-weathering, siliceous, mylonitic domains separated by less-deformed country rocks is well exposed on benches northeast of Alger Lakes (Figure 2). The more localized character of shear deformation within the Palmetto Formation may be a result of strain softening within these mylonitic domains.

The shear zone bifurcates northwest of Alger Lakes (Figure 2): one splay continues northwest across Mesozoic rocks toward the Kuna Crest segment at Helen Lake, and the other splay strikes north-northwest and follows the Paleozoic/Mesozoic contact through Parker Pass. Northwest of Parker Pass, the trace of the shear zone is mostly obscured by alluvium, but scattered outcrops of Paleozoic and Mesozoic rocks on the sides of Parker Pass valley contain mylonitic foliation typical of the shear zone.

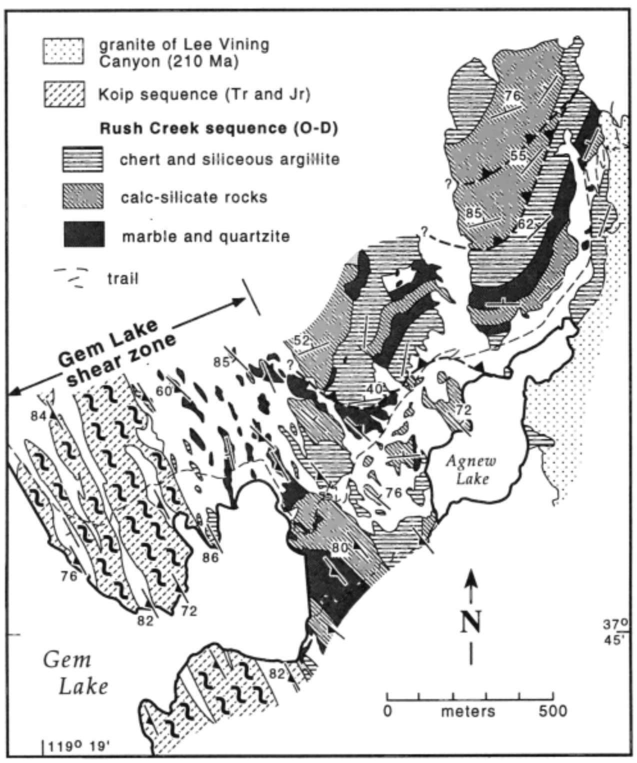

Figure 6. Generalized geologic map of the Gem Lake shear zone at Gem Lake, showing the breakup and overprinting of northeast trending structural grain in the Rush Creek sequence by the northwest trending Gem Lake shear zone (modified from *Strobel* [1986]).

Conditions of deformation. The metavolcanic rocks generally contain plagioclase, quartz, K-feldspar, biotite, chlorite, sericite, calcite, and epidote. A complex metamorphic and alteration history has been documented in the adjacent Ritter Range pendant by *Hanson et al.* [1993]. Within the shear zone, quartz porphyroclasts in silicic metavolcanic rocks may show indistinct core-and-mantle structure, and undulatory extinction and subgrains are evident in porphyroclast cores. Elongate quartz porphyroclasts are boudinaged, whereas feldspar porphyroclasts generally display extensional fractures and microfaults. These microstructures suggest deformation under subgreenschist facies conditions, near the lower limit of quartz crystal plasticity [*Simpson and De Paor*, 1991].

Dextral shear indicators. In the Gem Lake segment, dextral strike-slip deformation is indicated by porphyroclast asymmetries, S-C fabric, rotated veins, and asymmetric minor folds. Dextral shear indicators were observed at Gem Lake, Gem Pass, Alger Lakes, Koip Peak, southeast of Parker Pass, and at the northern end of Kuna Crest. At Gem Lake, asymmetric winged inclusions [*Hanmer and Passchier*, 1991] are prominent in crystal lithic tuffs and tuff breccias of the Koip sequence (Figure 7). Pressure-shadow wings with dextral asymmetry, delineated by recrystallized calcite, sericite, and quartz, are well developed around feldspar and quartz porphyroclasts (Figure 7a). Sericite concentrations on the high-pressure corners of porphyroclasts form quarter structures [*Hanmer and Passchier*, 1991], also indicating dextral shear (Figure 7b).

Many porphyroclast systems have a compound history, in which an inclusion with a sigma-type pressure shadow that originally formed with dextral asymmetry has been rotated in a clockwise direction (Figures 7a and 7b). These rotated inclusions are similar to delta-type porphyroclast systems described by *Passchier and Simpson* [1986]. However, the wings of the inclusions described here consist of a quartz-calcite-sericite mineral assemblage that precipitated in the pressure shadow, rather than material tectonically eroded from the rotating grain as in delta-type systems. These porphyroclast systems may indicate changing conditions during shear deformation, with relatively higher temperatures and/or slower strain rates (favoring recrystallization) alternating with lower temperatures and/or faster strain rates (favoring porphyroclast rotation) [*Hanmer and Passchier*, 1991].

Northwest of Gem Lake at Gem Pass (Figure 2), S-C fabric is well developed in fine-grained crystal tuff and sericite schist. Shear planes (C planes) striking N20-50W and dipping 80° SW are discrete, planar to anastomosing, and defined by segregations of quartz and phyllosilicates. Schistosity (S planes), defined by pressure-solution surfaces and sericite, is axial planar to crenulations with a dextral asymmetry. Synthetic shear bands (C' planes of *Berthé et al.* [1979]) with dextral offset are prominent in many sections and commonly contain syndeformational calcite with curved grains and grain shape preferred orientation indicating dextral shear.

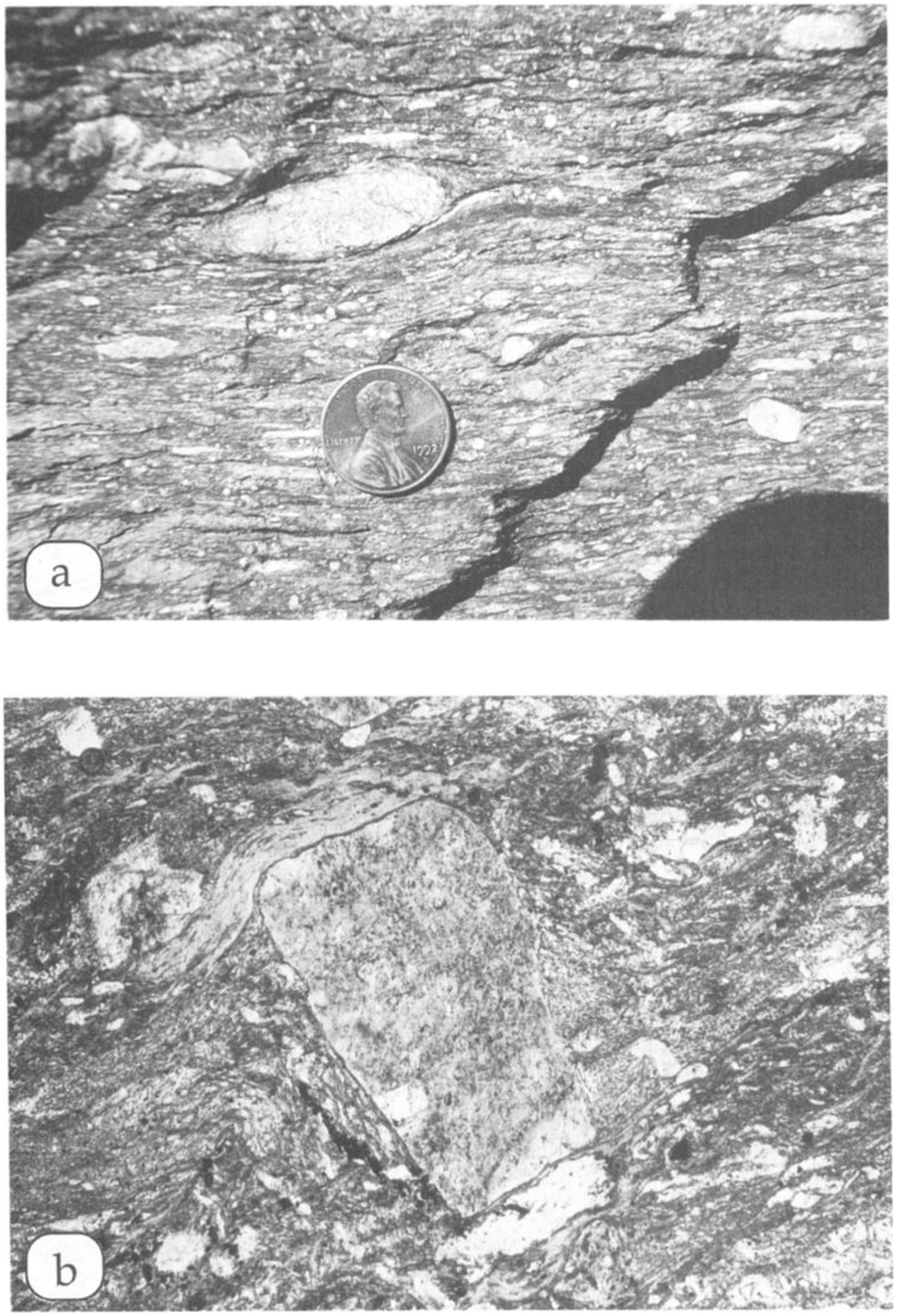

Figure 7. Deformation features in crystal-lithic lapilli tuff, Gem Lake segment, northeast shore of Gem Lake. (a) Winged lithic and porphyroclast systems indicating dextral shear. Small porphyroclast in lower right shows clockwise-rotated pressure shadows. (b) Photomicrograph of clockwise-rotated plagioclase porphyroclast. Field of view is 2 mm. Figures 7a and 7b are oriented horizontally, with top of photo to the southwest. (c) Steeply plunging lineation on foliation plane. Figure 7c is orientated vertically, parallel to foliation. (d) Photomicrograph of plagioclase porphyroclasts stretched vertically, parallel to steeply plunging lineation, with elongate calcite filling pressure shadow. Field of view is 2 mm. Figure 7d is oriented parallel to lineation and perpendicular to foliation.

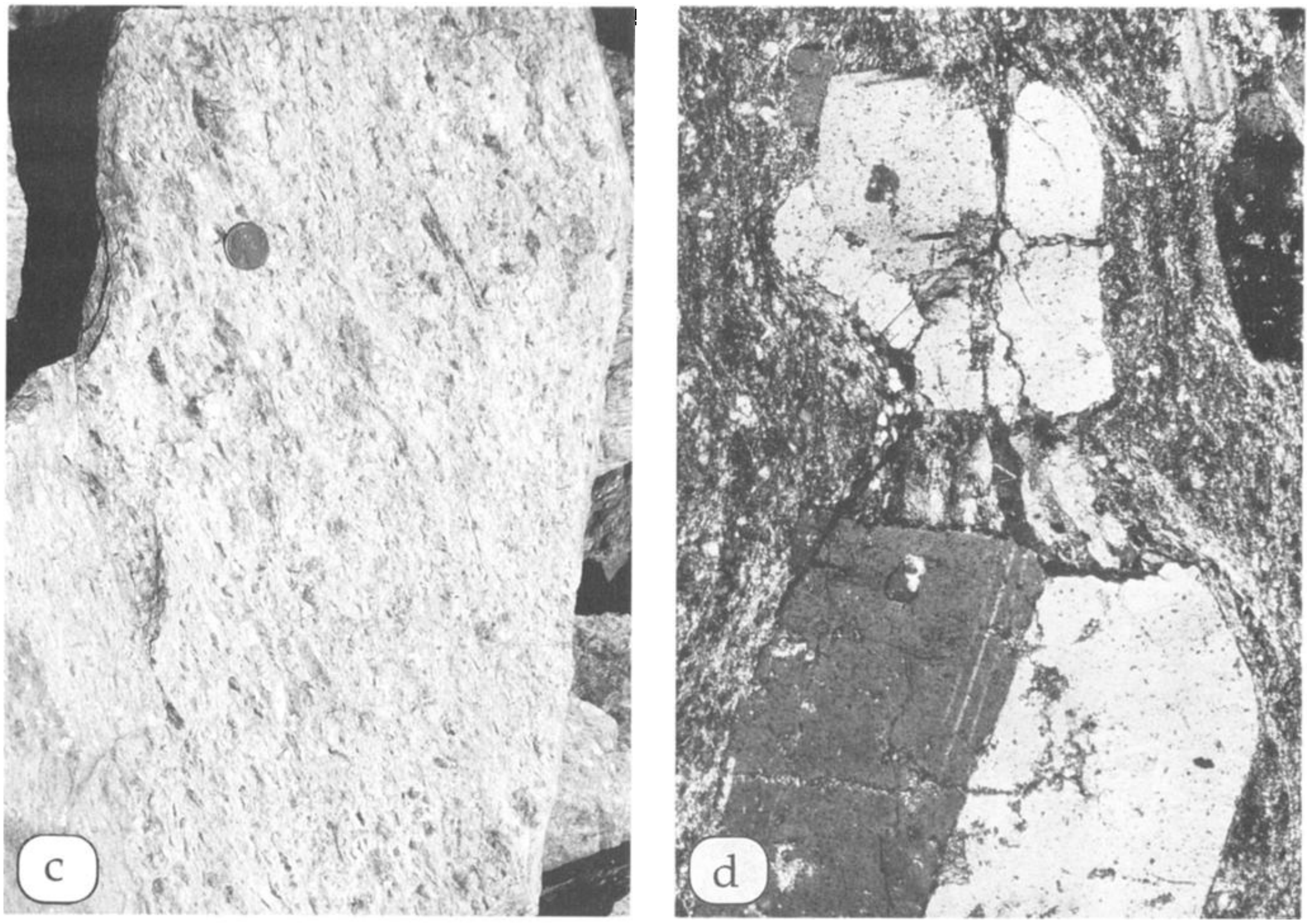

Figure 7. (continued)

Rotated veins and asymmetric folds of mylonitic foliation with a dextral displacement sense are locally prominent at both mesoscopic and microscopic scales, particularly in the Gem Lake area. Hinge lines of asymmetric folds plunge steeply to the northwest, parallel to the stretching lineation.

Stretching lineation. A prominent, northwest plunging stretching lineation in the Gem Lake segment (Figure 5) is evident on steeply southwest dipping foliation planes (Figure 7c). It is defined by elongate aggregates of phyllosilicates, extended lithic clasts, and extended quartz and feldspar porphyroclasts.

At Gem Lake, lithic clasts are fractured and symmetrically extended in the lineation direction, and the extension fractures are filled by calcite. Lineation-parallel thin sections show boudinaged and brittlely extended porphyroclasts (Figure 7d), which generally have symmetrical pressure shadows containing calcite, sericite, and quartz. This stretching lineation indicates symmetrical stretching in a subvertical direction, parallel to the rotation axis for dextral simple shear deformation.

Summary. In the Gem Lake segment, dextral strike-slip deformation is indicated by porphyroclast asymmetries, S-C fabric, rotated veins, and asymmetric minor folds observed on horizontal surfaces. Subvertical stretching is evidenced by symmetrically extended porphyroclasts and by steeply plunging stretching lineation. There is no consistent overprinting relationship between structures related to strike slip and those related to stretching.

Extension fractures and pressure shadows associated with the stretching lineation contain the same calcite-sericite-quartz mineral assemblage as the S-C fabric and the asymmetric porphyroclast systems associated with dextral shearing. In addition, feldspar and quartz porphyroclasts show similar brittle to brittle-ductile conditions of deformation in both stretching-parallel and strike-slip-parallel sections. We interpret these relations to indicate that dextral shearing and subvertical stretching in the Gem Lake segment were coeval. The Gem Lake segment is thus a transpressional shear zone in which the stretching direction is perpendicular to the slip direction.

Kuna Crest Segment

The Kuna Crest segment is characterized by a zone of prominently lineated rocks, exposed from the north end of Kuna Crest to the vicinity of Blacktop Peak (Figure 2). Although structures in the Kuna Crest segment indicate dominantly subvertical stretching, subordinate dextral structures are also present, and the Kuna Crest segment is considered to be a segment of the Gem Lake shear zone.

Stretching lineation in the Kuna Crest segment is best developed in siliceous wall rocks at or near the contact with the granodiorite of Kuna Crest; lineation is less well developed in volcanic rocks of the Koip sequence and is rarely visible in the granodiorite itself. Thus, although the Kuna Crest segment is spatially associated with the granodiorite of Kuna Crest, the intensity of deformation has been influenced significantly by wall-rock lithology. At the north end of Kuna Crest, the zone of most intense deformation follows the contact between the Palmetto Formation and the Sawmill Canyon sequence, rather than the granodiorite/wall-rock contact. Lineation is progressively less well developed in the Palmetto Formation to the east, but the decrease in deformation intensity is gradual, and lineation can be recognized locally as far east as Parker Pass valley.

Conditions of deformation. Stretching in the Kuna Crest segment occurred at relatively low temperatures, as indicated by the limited elongation of quartz porphyroclasts in rocks with a strongly deformed matrix. For example, a quartz porphyry dike involved in the shear zone has a strongly developed lineation defined by streaks of muscovite and biotite on foliation planes. However, large quartz phenocrysts (5-10 mm in diameter) in the porphyry are only slightly extended (axial ratios of 2:1). Steeply plunging symmetrical pressure-shadow wings around phenocrysts and foliation-parallel lattice-preferred orientation of quartz in the matrix suggest predominantly pure shear deformation.

In contrast, a dike of the granodiorite of Kuna Crest that intrudes the shear zone northeast of Kuna Lake (Figure 2) records a significantly higher temperature of deformation. In this dike, quartz forms elongate, multigrain ribbons, and K-feldspar porphyroclasts consist of highly elongate aggregates of subgrains showing evidence of grain-boundary migration recrystallization [e.g., *Simpson and DePaor,* 1991; *Hirth and Tullis,* 1992]. The higher temperature of deformation of this dike as compared to the surrounding country rock indicates that late deformation on the Kuna Crest segment was coeval with intrusion of dikes of the granodiorite of Kuna Crest.

Lineation and foliation. Bedding and foliation orientations in the Kuna Crest segment, and throughout the Kuna Crest area, strike N10E to N20W and dip steeply to the east (Figure 5). This contrasts with the rest of the NRP, in which the structural fabric dips predominantly to the southwest. As in the main Gem Lake shear zone, foliation is subparallel to and an intensification of regional structural fabric. Lineation plunges steeply to the south.

Stretching lineation associated with the Kuna Crest segment is particularly well exposed northeast of Kuna Lake, where quartz siltstone of the Palmetto Formation, a Jurassic(?) quartz porphyry dike (Figure 8), and a dike from the granodiorite of Kuna Crest are all moderately to poorly foliated but strongly lineated. Stretching lineation is defined by elongate aggregates of phyllosilicates and by segregations of quartz and feldspar. Foliation is predominantly defined by compositional and grain-size differences and consists of relict layering accentuated by subsequent metamorphic segregation.

West of Blacktop Peak, the granodiorite of Kuna Crest displays a well-developed, northwest striking, solid-state foliation subparallel to the pluton margin (Figure 9). The foliation is defined by highly elongate quartz and feldspar grains and biotite folia wrapping around feldspar grains. Rare K-feldspar porphyroclasts have sigma-type asymmetry indicating dextral shearing. A locally developed stretching lineation plunges steeply to the southeast, parallel to stretching lineation in the adjacent Sawmill Canyon sequence. Foliation is intense only within a few meters of the wall-rock

Figure 8. Extension lineation on subvertical foliation surfaces in quartz porphyry dike, Kuna Crest.

Figure 9. Solid-state foliation in granodiorite of Kuna Crest approximately 2 m from contact with wall rocks. View is northwest at a subvertical surface, located in cirque west-northwest of Blacktop Peak.

contact and decreases to a poorly developed magmatic(?) foliation within a few hundred meters. *Kistler* [1966a] mapped this area as the Cretaceous "sheared granodiorite of Koip Crest"; subsequently, *Bateman* [1992] included it in the Jurassic "sheared granites of Koip Crest and the South Fork of Bishop Creek." However, outside the shear zone these rocks are petrographically identical to the granodiorite of Kuna Crest. They are here considered to be Cretaceous granodiorite of Kuna Crest that has undergone localized solid-state deformation associated with the Kuna Crest segment of the Gem Lake shear zone.

Dextral deformation. A component of subhorizontal dextral simple shear within the Kuna Crest segment is indicated by rare asymmetric folds, rotated tension gashes, and locally developed S-C fabrics with shear planes parallel to regional foliation. Dextral shear indicators were observed at more than nine locations, primarily along the northern part of the Kuna Crest, near Helen Lake, and west of Blacktop Peak. However, structures indicative of dextral shear are much less prominent than in the Gem Lake segment, indicating that in the Kuna Crest segment subhorizontal shortening and subvertical stretching were the dominant deformation.

Relation of Kuna Crest segment to granodiorite of Kuna Crest. Complex and locally contradictory relations between intrusion of the granodiorite of Kuna Crest and deformation in the shear zone indicate that intrusion of the granodiorite at 91 Ma (U/Pb zircon age [*Stern et al.,* 1981]) was coeval with deformation in the Gem Lake shear zone.

The main mass of the granodiorite adjacent to the Kuna Crest segment displays a variably developed solid-state foliation parallel to the wall-rock contact but generally does not contain a prominent stretching lineation. Contact relations between deformed rocks of the shear zone and granodiorite vary along strike. South of the Kuna Crest, strongly lineated wall rocks locally form xenoliths within only slightly deformed granodiorite, and undeformed late pegmatite veins cut highly deformed wall rocks, indicating deformation prior to intrusion. However, near Helen Lake the granodiorite/wall-rock contact is a complex zone of interleaved, deformed granodiorite and foliated wall rock suggesting synintrusional deformation. Pegmatite veins in the wall rock at Helen Lake are boudinaged vertically, indicating synintrusional to postintrusion vertical stretching. West of Blacktop Peak, the granodiorite contains rare, steeply plunging folds delineated by felsite veins. Well-developed, steeply dipping, solid-state foliation in the granodiorite (described above) is axial-planar to these folds. Subhorizontal felsite dike swarms are locally prominent in this area, also demonstrating synemplacement to early postemplacement subvertical stretching.

Comparison of Kuna Crest Segment With Gem Lake Segment

Both the Gem Lake and Kuna Crest segments are dextral transpressional shear zones. Based on the relative development of small-scale structures, dextral strike slip was dominant in the Gem Lake segment, and subvertical stretching was dominant in the Kuna Crest segment. Both shear zones exhibit a similar structural style, involving distributed deformation which reactivated an older regional structural fabric.

Both the Gem Lake and Kuna Crest segments were active before and during emplacement of Late Cretaceous plutons. The Kuna Crest segment, as discussed above, was active during and after emplacement of the granodiorite of Kuna Crest at 91 Ma. The Gem Lake segment does not intersect Cretaceous granitoids, but $^{40}Ar/^{39}Ar$ dating of syntectonic amphibole to the southeast in the Ritter Range segment of the shear zone (Figure 4) indicates deformation at 85 Ma [*Sharp et al.,* 1993], probably synchronous with postemplacement deformation of the granodiorite of Kuna Crest.

The Gem Lake and Kuna Crest segments display an anastomosing map pattern (Figure 2). A splay of the Gem Lake segment trends obliquely into the Kuna Crest segment south of Helen Lake, and at the north end of Kuna Crest the Gem Lake and Kuna Crest segments appear to merge. This anastomosing map pattern, combined with the similarities in deformation, structural style, and timing, indicates that the Kuna Crest and Gem Lake segments are parts of the same shear zone.

Regional Characteristics of the Gem Lake Shear Zone

The Gem Lake shear zone includes the Gem Lake segment, the Kuna Crest segment, the Ritter Range segment, and adjacent splays (Figure 4). The Gem Lake shear zone probably correlates directly with nearby shear zones to the north and south and generally with a much larger set of similar-trending shear zones collectively called the Sierra Crest shear zone system [*Tikoff,* 1994; *Tikoff and Greene,* 1994]. The following sections detail the extent, displacement, and timing of deformation associated with the Gem Lake shear zone. Subsequent sections describe the connections and correlations between the Gem Lake shear zone and the proposed Sierra Crest shear zone system, contrast this system with other proposed shear zones in the central and southern Sierra Nevada, and discuss the relation of shear zone deformation to pluton emplacement.

Northward Continuation

North of Kuna Crest, a prominent solid-state foliation that is on strike with the Gem Lake shear zone is present in both the Half Dome Granodiorite and the granodiorite of Kuna Crest. A steeply southeast plunging extension lineation is well developed only near the granodiorite/wall-rock contact. Quartz ribbons parallel to elongate feldspar and mafic minerals indicate predominantly solid-state deformation.

The contact between these deformed granitoids and wall rocks of the Koip sequence is well exposed 1 km southwest of Gaylor Peak (Figure 4), where both the granodiorite of Kuna Crest and the wall rocks are highly deformed. Protomylonite with local S-C fabric is developed in the granodiorite, and complex deformation features including ductilely deformed pseudotachylite(?) layers are present in the Koip sequence. Five kilometers northwest of Gaylor Peak at Sawmill Canyon, a prominent downdip lineation is developed in the Jurassic wall rocks of the Sawmill Canyon sequence [*Schweickert and Lahren,* 1993a]. These relations suggest that the Gem Lake shear zone may continue to the north for some distance along the west edge of the Saddlebag Lake pendant, involving both the Koip and Sawmill Canyon sequences and Late Cretaceous granitoids of the Tuolumne Intrusive Suite [*Tikoff,* 1994; *Tikoff and Greene,* 1994].

Ritter Range Segment

South of the NRP, the trace of the Gem Lake shear zone is concealed beneath Tertiary volcanic cover, but 5 km along strike to the southeast in the Ritter Range pendant (Figure 4), anastomosing domains of highly sheared rock occur in the basal part of the Koip sequence and along the Paleozoic/Mesozoic contact. The Ritter Range segment contains orange-weathering, siliceous mylonitic rocks with sigma-type inclusion and porphyroclast systems indicating dextral shearing. A locally well-developed S-C fabric, with shear planes striking N40-60W and dipping vertically, also shows dextral shearing. Stretching lineation and strain measurements in the younger volcanic section to the west indicate strong flattening deformation and vertical stretching [*Tobisch et al.,* 1977]. The $^{40}Ar/^{39}Ar$ dating of synkinematic minerals within the Ritter Range segment has yielded ages of 85 Ma (hornblende) and 81 Ma (biotite and sericite) [*Sharp et al.,* 1993].

At Minaret Summit, on the southeast edge of the Ritter Range pendant (Figure 4), lenses of foliated crinoidal marble are imbricated with Mesozoic metavolcanic rocks. These marble lenses contain chert nodules with prominent pressure-shadow wings indicating dextral shear (Figure 10) and are identical to fossiliferous marble lenses exposed in the Gem Lake shear zone northwest of Alger Lakes (described below). Dextral transpressional deformation related to the Gem Lake shear zone can thus be traced as far south as Minaret Summit on the southeast edge of the Ritter Range pendant.

Amount of Displacement

The magnitude of dextral displacement on the Gem Lake shear zone is difficult to constrain because displacement was predominantly parallel to the regional trends of structures. However, an estimate of displacement is provided by isolated lenses of fossiliferous marble imbricated with the Palmetto Formation in the shear zone northwest of Alger Lakes (Figure 2) [*Greene,* 1995]. These lenses of marble contain a late Paleozoic shallow-water fauna indicating a general age range from Late Mississippian through mid-Permian (J.T. Dutro, written communication, 1988) and conodont fragments compatible with a Carboniferous age (J. Repetski, oral communication, 1991).

Structurally imbricated lenses of crinoid-bearing marble that are very similar to those at Alger Lakes are also exposed at Minaret Summit [*Huber and Rinehart,* 1965], where they contain mylonitic foliation and chert nodules with prominent dextral asymmetry (Figure 10). The same distinctive crinoid-bearing marble is exposed at Mammoth Rock (Figure 4), at Pappas prospect (3 km east of Mammoth Rock), and in the Mount Morrison pendant [*Rinehart and Ross,* 1964]. All these exposures have been correlated with the Pennsylvanian Mount Baldwin Marble in the Mount Morrison pendant, which consists of a distinctive, dark gray marble containing crinoid columnals and chert nodules [*Rinehart and Ross,* 1964; *Huber and Rinehart,* 1965; *Kistler and Nokleberg,* 1979; *Greene and Dutro,* 1991].

Correlation of the upper Paleozoic marble lenses at Alger Lakes with those at Minaret Summit suggests a minimum of 20 km of dextral displacement. If the marble lenses at Minaret Summit were displaced from the Mount Baldwin Marble in the Mount Morrison pendant, there is a possibility of at least 7 km of additional displacement between Minaret Summit and the north end of the Mount Morrison pendant (Figure 4). Because the isolated lenses of marble lie entirely within the shear zone, the extent of the marble lenses probably does not reflect the total displacement across the shear zone, and the above estimates are therefore minimum offsets.

An alternative possibility is that the Pennsylvanian(?) marble lenses at Alger Lakes are depositional remnants of a more widespread upper Paleozoic Antler overlap sequence. This alternative is unlikely, however, for the following reasons: (1) the marble lenses occur only within the Gem Lake shear zone, in association with widespread evidence of dextral shearing; (2) the marble lenses occur only as rare, isolated slices structurally imbricated with surrounding units; and (3)

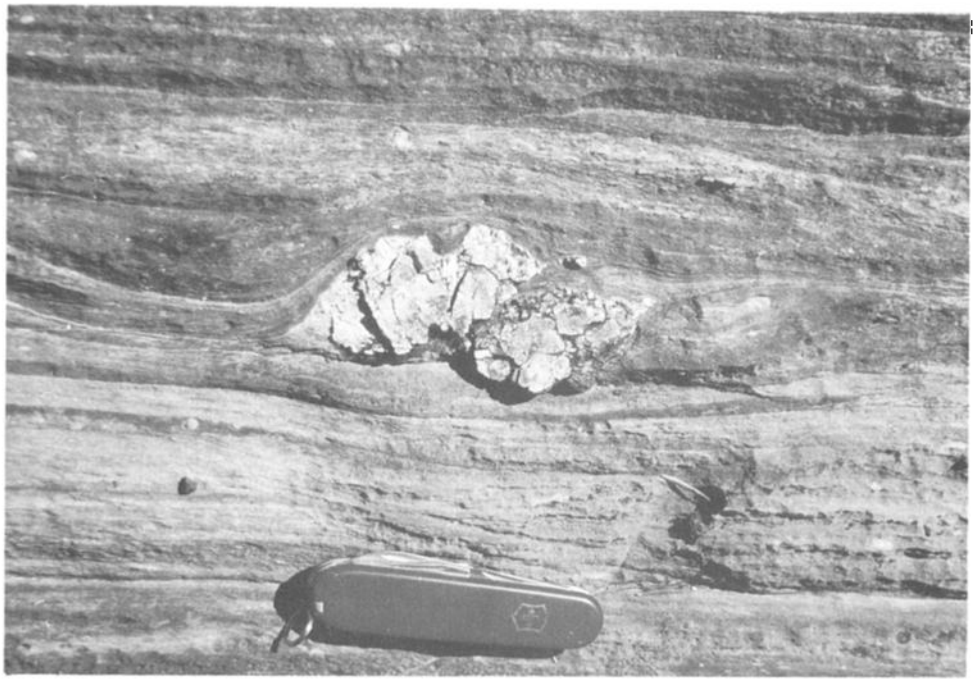

Figure 10. Ductile flow around chert inclusion in marble, Ritter Range segment, Minaret Summit. Photo is oriented horizontally, with top to the southwest. Light-colored wings attached to upper right and lower left of inclusion are composed of white calcite initially formed in the pressure shadows of the inclusion during dextral shearing [*Hanmer and Passchier,* 1991].

the marble lenses are not associated with other units of the upper Paleozoic section (in contrast to all known parautochthonous exposures of the Mount Baldwin Marble). However, if the marble lenses are in fact locally derived remnants, then dextral displacement on the Gem Lake shear zone could be much less.

Timing of Displacement

Although the exact timing of displacement on the Gem Lake shear zone is unknown, available age constraints indicate that the Gem Lake shear zone was active in early Late Cretaceous time, from before 91 Ma to possibly as young as 76 Ma. Field relations in the NRP (discussed above) demonstrate that the Gem Lake shear zone was active during intrusion of the granodiorite of Kuna Crest at 91 Ma. However, the metamorphic rocks in the NRP show evidence of significantly more shear deformation than the granodiorite. Ductile shear fabrics, asymmetric folds and porphyroclasts, and extension lineations are all prominent in metamorphic rocks in the Gem Lake shear zone but only locally present in the granodiorite. In addition, inclusions of protomylonitic wall rocks occur in much less deformed granodiorite near the granite/wall rock contact on Kuna Crest. These observations indicate that initial deformation in the Gem Lake shear zone preceded intrusion of the granodiorite.

North of the NRP, local solid-state foliation that is on strike with the Gem Lake shear zone is present in the Half Dome Granodiorite, which has an age between 88 and 86 Ma [*Bateman,* 1992]. In metavolcanic rocks in the Ritter Range segment of the shear zone, *Sharp et al.* [1993] obtained $^{40}Ar/^{39}Ar$ ages of 85 Ma for syntectonic amphibole and 80 Ma for syntectonic biotite and white mica.

South of Minaret Summit, the Gem Lake shear zone is probably continuous with the Rosy Finch shear zone (discussed in detail below). The Rosy Finch shear zone is exposed in the Lake Edison Granodiorite, which has a concordant U/Pb age of 88±1 Ma [*Tobisch et al.,* 1995], and in the Mono Creek Granite, which has yielded a discordant U/Pb age of 88 Ma and a concordant U/Pb age of 76 Ma [*Stern et al.,* 1981]. Displacement on the Rosy Finch shear zone is considered to be synmagmatic to early postmagmatic [*Tikoff and Teyssier,* 1992; *Tobisch et al.,* 1995], and *Tobisch et al.* [1995] reported Ar/Ar ages of 87 Ma on metamorphic hornblende and 83 Ma on metamorphic biotite from within the shear zone in the Lake Edison pluton. Thus late displacement on a continuous Gem Lake-Rosy Finch shear zone is younger than 88 Ma and could be as young as 76 Ma. Dextral displacement on the Rosy Finch shear zone is probably in the range of 1.2-8 km (B. Tikoff, personal communication, 1994), which is substantially less than the minimum of 20 km of displacement suggested here for the Gem Lake shear zone. This is consistent with the interpretation that displacement on the Gem Lake shear zone in the NRP began prior to intrusion of the Late Cretaceous plutons in which the Rosy Finch shear zone is exposed.

In summary, available age data indicate that the Gem Lake shear zone was active from before 91 Ma to possibly as young as 76 Ma. These data do not constrain the beginning of deformation in the shear zone, which is only known to be younger than 201 Ma. Metavolcanic rocks of this age underlie the Sawmill Canyon sequence [*Schweickert et al.,* 1994], which is the youngest metamorphic unit involved in the shear zone.

However, at least two lines of evidence suggest that displacement on the shear zone probably occurred predominantly in early Late Cretaceous time.

1. A minimum dextral displacement of 20 km is suggested here for the Gem Lake shear zone. At an average slip rate of 5 mm/year, this much displacement could be achieved in 4 m.y. and twice this displacement in less than 10 m.y. Thus the age range of dated deformation in the Gem Lake shear zone (>91 Ma to 80 Ma) is more than sufficient to account for the suggested displacement.

2. Reconstructions of Cretaceous plate convergence vectors between North America and Farallon plates [*Engebretson et al.,* 1985; *Glazner,* 1991; *Tobisch et al.,* 1995] indicate that a large dextral tangential component of convergence across the plate boundary developed only after about 100 Ma. Oblique convergence in modern plate boundary settings is known to result in strain partitioning and strike-slip deformation within the arc [e.g., *Jarrard,* 1986; *Cashman et al.,* 1992; *McCaffrey,* 1992; *Teyssier et al.,* 1995], and it seems reasonable to interpret the dextral transpressional Gem Lake shear zone in the Sierra Nevada magmatic arc as a manifestation of post-100 Ma dextral oblique convergence.

Tobisch et al. [1995] have recently suggested that a transition from predominantly contractional deformation to dextral transpressional deformation occurred in the eastern Sierra Nevada at around 90 Ma, based on dating of contractional shear zones in the west-central Sierra Nevada and the age of deformation in the Rosy Finch shear zone. We suggest that this transition may have occurred somewhat earlier, in the range of 110-100 Ma, based on the evidence presented here for significant activity on the Gem Lake shear zone prior to 91 Ma.

Regional Tectonic Implications

Correlation of the Gem Lake Shear Zone

South of Minaret Summit, the Gem Lake shear zone is concealed by Quaternary volcanic rocks of Mammoth Mountain, but sheared granite and wall rocks associated with the dextral Rosy Finch shear zone have been reported along the northeast edge of the Mono Creek pluton (Figure 11), 10 km to the southeast of Minaret Summit [*Tikoff and Teyssier,* 1992; *Tikoff,* 1994].

The Rosy Finch shear zone is 3-4 km wide through the central part of the Mono Creek pluton, displays consistent dextral shear indicators throughout, and is synemplacement to early postemplacement [*Tikoff and Teyssier,* 1992]. The shear zone continues southeastward through the Lake Edison pluton [*Lockwood and Lydon,* 1975], the Lamarck pluton, and into the northern part of the Evolution Basin pluton (Figure 11) (B. Tikoff, personal communication, 1994). The Rosy Finch shear zone developed to accommodate active dextral deformation as these Late Cretaceous plutons intruded and cooled. The Rosy Finch shear zone as presently exposed probably records the last increments of dextral deformation on an older shear zone that may, like the Gem Lake shear zone, have had significant displacement prior to intrusion of Late Cretaceous granitoids.

South of the Rosy Finch shear zone, northwest trending zones of sheared granitoids and metavolcanic rocks as young as 131 Ma (U/Pb age) [*Tobisch et al.,* 1986] have been reported in the Mount Goddard pendant (Figure 11) [*Bateman,* 1965, 1992; *Bateman and Moore,* 1965; *Moore,* 1978; *Tobisch et al.,* 1986; *Saleeby et al.,* 1990]. Although the sense of displacement in these sheared rocks is presently unknown, significant subvertical stretching consistent with that observed in the Gem Lake shear zone has been reported by *Tobisch et al.* [1986].

Northwest trending zones of sheared granitoids have also been mapped north of the Oak Creek pendant (Figure 11) [*Moore,* 1963; *Saleeby et al.,* 1990] and are separated from the Mount Goddard pendant only by the Late Cretaceous Cartridge Pass pluton [*Moore,* 1963]. Penetrative ductile deformation in the Oak Creek pendant itself [*Longiaru,* 1987; *Saleeby et al.,* 1990] suggests that the zone of shearing could conceivably continue through the Oak Creek pendant and into the Owens Valley. Deformation in the Oak Creek pendant and associated sheared granitoids has been dated at between 110 and 105 Ma (U/Pb) [*Saleeby et al.,* 1990].

The degree of continuity of these various shear zones and sheared granitoids is unknown. Nevertheless, a nearly continuous system of middle Cretaceous shear zones can be traced from the Saddlebag Lake pendant to at least the Oak Creek pendant, a distance greater than 150 km (Figure 11). A dextral transpressional shear zone system of this extent would have important implications for middle Cretaceous tectonics and pluton emplacement in the Sierra Nevada.

We propose to call this system of distributed dextral shearing the Sierra Crest shear zone system [*Tikoff,* 1994; *Tikoff and Greene,* 1994]. This is intended as a collective term for locally defined, but possibly related, middle Cretaceous dextral shear zones in the eastern Sierra Nevada including, but not limited to, the Gem Lake, Rosy Finch, and associated shear zones discussed above.

Other Proposed Shear Zones in the Central and Southern Sierra Nevada

The Gem Lake shear zone and its possible continuations provide direct field evidence for a dextral shear zone system of regional extent in the central and eastern Sierra Nevada. As noted earlier, similar dextral shear zones have been suggested by a number of workers based on other lines of evidence.

IBB 2 and IBB 3. Two intrabatholithic dextral faults, termed Intrabatholithic Breaks 2 and 3 (IBB 2 and IBB 3) by *Kistler* [1990, 1993] and the Axial and Eastern Batholithic Breaks (AIB and EIB) by *Saleeby and Busby* [1993], have been proposed on the basis of apparent dextral steps in the trace of the Sr_i=0.706 isopleth (Sr_i = initial ratio $^{87}Sr/^{86}Sr$). The Gem Lake and associated shear zones lie between the traces of these proposed intrabatholithic faults (Figure 12). The proposed Mojave-Snow Lake fault coincides with IBB 2 along part of its length.

The precise locations of these intrabatholithic breaks are not well constrained by published initial strontium data points, and *Kistler's* [1993] proposed trace of IBB 3 conflicts

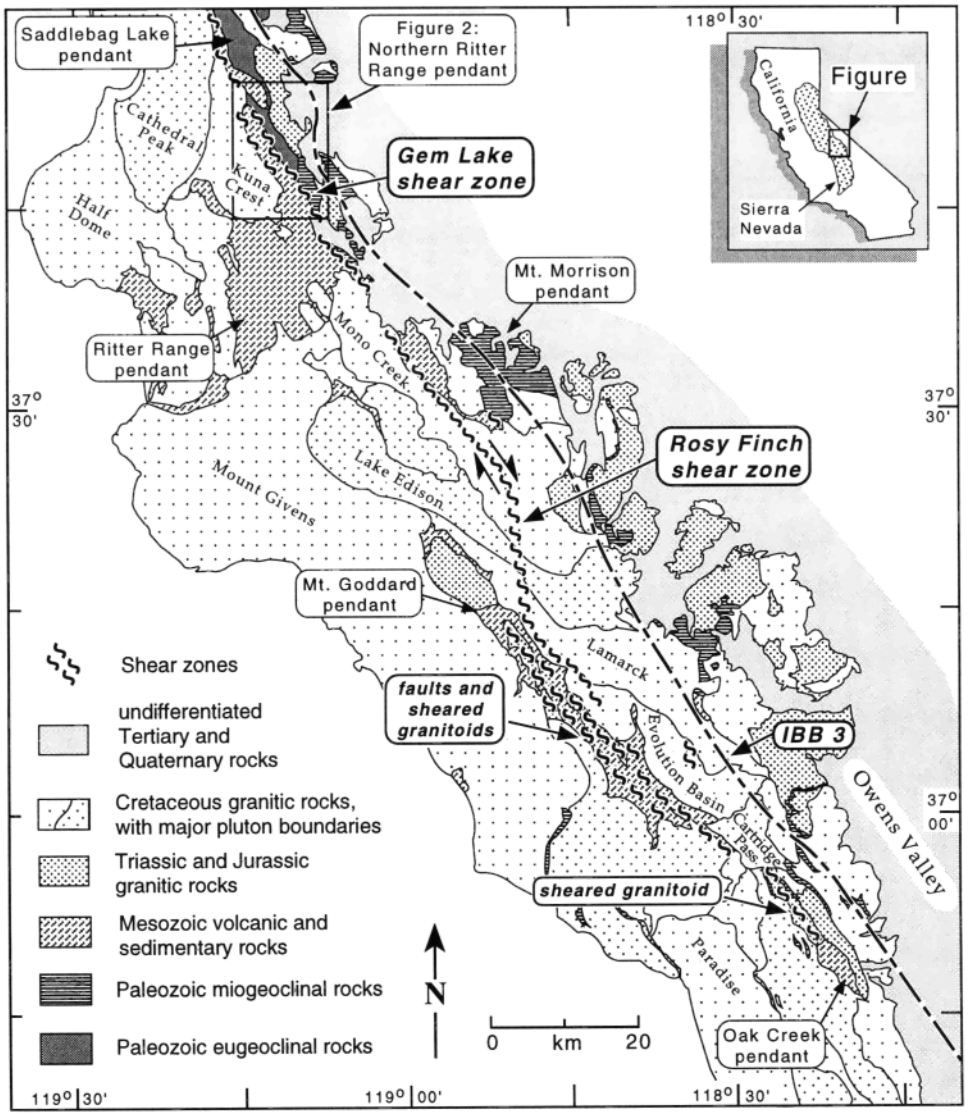

Figure 11. The Gem Lake shear zone and possible continuations in the eastern Sierra Nevada that comprise the proposed Sierra Crest shear zone system. Names of selected Late Cretaceous plutons are shown; ages are as follows: Kuna Crest, 91 Ma U/Pb; Mono Creek, 88 Ma, 76 Ma U/Pb [*Stern et al.*, 1981]; Lake Edison, 88±1 Ma U/Pb [*Tobisch et al.*, 1995]; Lamarck, 90 Ma U/Pb [*Stern et al.*, 1981]; Evolution Basin, 85, 80, and 79 Ma K/Ar [*Evernden and Kistler*, 1970]. Figure 11 is modified from *Bateman* [1992], *Saleeby et al.* [1990], and B. Tikoff (unpublished mapping, 1994); trace of IBB 3 is from *Kistler* [1993].

with known field relations in the Saddlebag Lake pendant [*Schweickert and Lahren*, 1993a, b] and the Mount Morrison pendant [*Greene et al.*, 1995]. Evidence for correlation of Triassic granites across the proposed trace of IBB 3 [*Kistler*, 1993] is equivocal at best, and there is no documented evidence of dextral shearing along the proposed fault trace. An alternative location for IBB 3 would be the Sierra Crest shear zone system. Published initial strontium data points [*Kistler*, 1993] are compatible with this suggestion, although the 90 km of dextral displacement postulated by *Kistler* [1993] for IBB 3 is substantially larger than the displacement we infer for the Gem Lake shear zone.

Possibly, a broad zone of distributed dextral deformation, involving numerous anastomosing strike-slip shear zones, developed along the axis of the Sierra Nevada in middle Cretaceous time. The Gem Lake shear zone and associated structures of the Sierra Crest shear zone system may be preserved remnants of such deformation. The northward offset of the Sr_i=0.706 isopleth could in part reflect this distributed deformation, rather than being the result of large offset on two discrete fault traces as presently proposed [*Kistler*, 1993].

Mojave-Snow Lake fault. The Mojave-Snow Lake fault (Figure 12), with up to 400 km of dextral displacement, has been proposed on the basis of stratigraphic correlation of miogeoclinal rocks and Jurassic intrusive rocks in the Snow Lake pendant with rocks of the Mojave Desert [*Lahren and Schweickert*, 1989; *Lahren et al.*, 1990; *Schweickert and Lahren*, 1990]. The trace of this proposed fault is near the axis

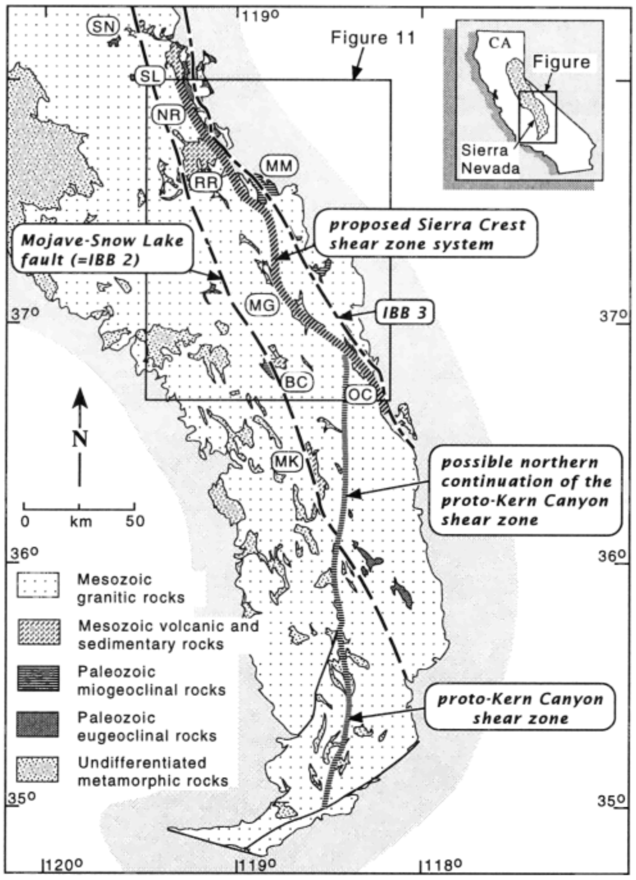

Figure 12. Proposed dextral shear zones in the central and southern Sierra Nevada. Abbreviations are: BC, Boyden Cave pendant; MG, Mount Goddard pendant; MK, Mineral King pendant; MM, Mount Morrison pendant; NR, Northern Ritter Range pendant; OC, Oak Creek pendant; RR, Ritter Range pendant; SL, Saddlebag Lake pendant; SN, Snow Lake pendant. Figure 12 is modified from *Jennings* [1977], with data from *Schweickert and Lahren* [1991], *Kistler* [1993], and *Saleeby and Busby* [1993].

of the Sierra Nevada batholith, approximately coincident with the position of IBB 2 [*Kistler,* 1993].

A dextral shear zone of middle Cretaceous age in the Mineral King pendant [*Saleeby and Busby,* 1993] and sheared granitoids of middle Cretaceous age in the Boyden Cave pendant [*Saleeby et al.,* 1990] occur near or along the proposed trace of the Mojave-Snow Lake fault. Steeply plunging stretching lineations of probable middle Cretaceous age that are present in these and many other pendants in the southern Sierra Nevada [*Saleeby et al.,* 1990; *Saleeby and Busby,* 1993] are consistent with transpressional deformation.

Lahren et al. [1990] concluded that displacement on the Mojave-Snow Lake fault occurred after 148 Ma (the age of dikes in the Snow Lake pendant that are correlated with the Independence dike swarm) and before about 110 Ma (the age of granitic plutons that are interpreted to have intruded and obscured the trace of the fault). These timing constraints suggest that displacement on the Mojave-Snow Lake fault occurred before the last phase of deformation in the Gem Lake shear zone. Possibly, an early phase of displacement on the Gem Lake shear zone was synchronous with displacement on the Mojave-Snow Lake fault, and the Gem Lake shear zone was later reactivated during intrusion of the Late Cretaceous plutons. In this case, the Gem Lake shear zone might have been a subsidiary strand of a Mojave-Snow Lake fault system, analogous to the various strands of the present-day San Andreas fault system [*Greene and Dutro,* 1991]. Other possibilities are (1) the Mojave-Snow Lake and Gem Lake shear zones do not overlap in time and are unrelated structures, and (2) displacement on the Mojave-Snow Lake fault may have been younger than is presently believed.

Proto-Kern Canyon shear zone. The proto-Kern Canyon shear zone (Figure 12) is a north trending, dextral shear zone exposed for more than 130 km in the southern Sierra Nevada [*Busby-Spera and Saleeby,* 1990; *Saleeby,* 1992]. The shear zone was active between about 105 Ma and 83 Ma, based on U/Pb dating of synkinematic and postkinematic intrusive rocks [*Busby-Spera and Saleeby,* 1990]. Sheared granitoids that are probably associated with a northward continuation of the proto-Kern Canyon shear zone are separated from similar sheared rocks in and adjacent to the Oak Creek pendant only by the Mount Whitney and Paradise plutons (83-86 Ma U/Pb) [*Moore,* 1981; *Chen and Moore,* 1982; *Moore and Sisson,* 1985]. This suggests the possibility of a connection between the shear zones prior to emplacement of the Mount Whitney intrusive suite, as originally proposed by *Schweickert* [1981]. *Tikoff and Greene* [1994] reported dextral shearing in the Mount Whitney intrusive suite and suggested that the proto-Kern Canyon shear zone be considered a part of the Sierra Crest shear zone system.

Relation to Pluton Emplacement

Timing constraints discussed above indicate that displacement on the Gem Lake shear zone was synchronous with intrusion of Late Cretaceous plutons of the Tuolumne Intrusive Suite (which includes the granodiorite of Kuna Crest and the Half Dome Granodiorite) and the John Muir Intrusive Suite (which includes the Lake Edison Granodiorite and the Mono Creek Granite). Plutons of these Late Cretaceous intrusive suites appear to have intruded the active Gem Lake and Rosy Finch shear zones and to have been subsequently deformed in the shear zones.

The Gem Lake shear zone thus provides direct field evidence for dextral transpressional deformation in the central eastern Sierra Nevada during the intrusion of Late Cretaceous granitoids and strengthens the case for a genetic link between dextral faulting and emplacement of Late Cretaceous plutons, as proposed by *Glazner* [1991], *Saleeby* [1991], and *Tikoff and Teyssier* [1992, 1993a], among others.

Evidence for major dextral transpressional deformation is locally recorded in wall-rock pendants as described here (e.g., the Gem Lake shear zone), whereas only the minor postemplacement phase of this deformation is recorded in the plutons themselves (e.g., the Rosy Finch shear zone). We speculate that emplacement and cooling of Late Cretaceous plutons may have substantially altered the rheology of the Sierra Nevada block, welded the shear zones, and possibly resulted in the transfer of dextral displacement from the arc to forearc or back arc regions.

Conclusions

In the Gem Lake shear zone, dextral shearing and subvertical stretching associated with horizontal shortening are directly related and resulted from dextral transpressional deformation. Widespread evidence exists for dextral strike-slip and/or contractional deformation with subvertical stretching during middle Cretaceous time in the central and southern Sierra Nevada. Other examples include the Rosy Finch shear zone, the proto-Kern Canyon shear zone, sheared rocks in the Saddlebag Lake, Mount Goddard, Oak Creek, Mineral King, and Boyden Cave pendants, and sheared granitoids in and adjacent to the Mount Whitney intrusive suite. While there is as yet insufficient data to demonstrate conclusively that all of this deformation is directly related, the evidence is consistent with the hypothesis that the middle Cretaceous Sierra Nevada was characterized by distributed dextral transpressional deformation, with numerous active shear zones that are now only locally preserved in metamorphic pendants and older plutons bordering the Late Cretaceous batholith.

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