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Early Cretaceous intra-arc ductile strain in Triassic-Jurassic and Cretaceous continental margin arc rocks, Peninsular Ranges, California

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Abstract. The Cuyamaca-Laguna Mountain shear zone (CLMSZ) lies along the axis of the Peninsular Ranges batholith, separating it into an eastern and western plutonic zones. The shear zone involves Triassic-Jurassic and Early Cretaceous plutonic units which intruded the Triassic Julian Schist and transects the eastern edge of a cryptic lithospheric boundary, separating oceanic crust on the west from continental crust on the east. The Julian Schist crops out on either side of the cryptic lithospheric boundary and is interpreted to represent an overlap sequence. This structural/stratigraphic relationship indicates that the contrasting lithospheric types must have been juxtaposed prior to approximately the Triassic time, and as a result, the CLMSZ probably developed in an intra-arc setting. At least two periods of deformation produced the polygenetic CLMSZ. Structures that formed during D_1 include S_1 and L_1. In Triassic-Jurassic and Early Cretaceous orthogneisses, S_1, a pervasive NW striking and NE dipping mylonitic gneissosity, obliterates nearly all traces of an older magmatic fabric. L_1 plunges steeply to the NE, lies within the plane of S_1, and is locally a well-developed stretching lineation. D_1 structures can be traced from the ~115 Ma Oriflamme Canyon protomylonite into the adjacent Julian Schist and are represented by a well developed S-C mylonitic structures indicative of NE-SW contraction. D_1 structures in the Oriflamme Canyon protomylonite and in the ~118 Ma Pine Valley granodiorite developed while these plutons were incompletely solidified. Hence D_1 probably occurred between ~118 and ~115 Ma and had culminated in the 105 My emplacement of the Las Bancas tonalite. Normal convergence, ~125 to 115 Ma, between the North American and Farallon plates is coincident with D_1 and the syntectonic emplacement of the Pine Valley granodiorite and the Oriflamme Canyon protomylonite. This relationship suggests that the mechanically weak, thermally and melt-softened cryptic lithospheric interface between oceanic and continental lithosphere may have yielded during the normal convergence event, resulting in the concentration of strain into the CLMSZ during arc magmatism. Such a conclusion underscores the possibility of using intra-arc structures to deduce convergence patterns, as elegantly argued in several recent papers. A >12-km long normal sense shear zone transects D_1 structures and formed during D_2. Mesoscopic structure associated with the normal sense shear zone includes S_2, L_2, and C_2. D_2 structures are the record of NE-SW extension between ~105- and ~94 Ma. They may be related to the vertical loading of the CLMSZ by the hanging wall block of the westward verging Santa Rosa and Borrego Springs mylonite belts or they may represent an early, local response to magmatically and structurally overthickened, gravitationally unstable crust. In the latter interpretation, D_2 structures are the harbingers of Tertiary-aged, gravity-driven collapse of the SW Cordilleran margin.

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Introduction

Magmatic arcs developed along continental margins are complex systems which respond in various ways to changing plate convergence patterns [*Dewey*, 1980; *Royden*, 1993]. For example, *Royden* [1993] showed that the retreating subduction boundaries (e.g. trench rollback) are produced when the rate of overall convergence is less than the rate of subductoin. In such a setting the transmission of horizontal compressive stress across the plate boundary is small, and resulting deformation in the magmatic arc of the overriding plate is achieved by horizontal extension. In contrast, when convergence of two plates is orthogonal and the overall convergence is greater than the rate of subduction, deformation in the adjacent magmatic arc will be by horizontal contraction [*Dewey*, 1980; *Royden*, 1993]. The analyses of *Dewey* [1980] and *Royden* [1993] imply that some structures developed within magmatic arcs may faithfully record changing plate convergence patterns. In this paper we describe structural data from the Cuyamaca-Laguna Mountain shear zone of the Peninsular Ranges batholith, southern California, which we believe are the record of changing plate convergence patterns between the North American and Farallon plates.

Prebatholithic and batholithic rocks

Plutonic rocks of the Peninsular Ranges batholith are subdivided into western and eastern plutonic zones zones [e.g., *Silver et al.*, 1979; *Todd and Shaw*, 1985; *Walawender et al.*, 1990, 1991]. Variably deformed Cretaceous-aged gabbroic to tonalitic bodies with U/Pb zircon ages mostly ranging from ~120 to 105 Ma make up the western zone [*Silver et al.*, 1979; *Silver and Chappell*, 1988; *Walawender et al.*, 1990, 1991]. These plutons intrude the variably deformed Late Jurassic to mostly Early Cretaceous Santiago Peak Volcanics on the west and the Triassic Julian Schist on the east [*Gastil et al.*, 1978; *Todd et al.*, 1988; *Anderson*, 1991; *Kimbrough et al.*, 1991; *Meeth*, 1993].

In contrast to the western zone the eastern zone includes mostly undeformed granodioritic to granitic plutons ranging in age from 105 to 89 Ma [*Silver et al.*, 1979; *Silver and Chappell,* 1988; *Walawender et al.,* 1990, 1991]. Plutons of the eastern zone clearly postdate western zone plutons and were emplaced into the multiply deformed Triassic Julian Schist and Precambrian (?) to lower Paleozoic miogeoclinal rocks of the eastern Peninsular Ranges [*Gastil et al.*, 1978; *Todd et al.*, 1988; *Walawender et al.*, 1990, 1991; *Thomson*, 1991].

The boundary between the western and eastern plutonic zone is defined by an arc-parallel step in radiometric ages. Coincident with this boundary is a series of geochemical, geophysical and petrological discontinuities. A pronounced gravity contrast [*Oliver*, 1980], variations in $\delta^{18}O$ and Sr_i isotopes [*Early and Silver*, 1973; *Taylor and Silver*, 1978], and differences in petrology [*Larsen*, 1948] suggest that the western zone is underlain by predominantly oceanic crust, whereas the eastern zone is underlain by transitional to continental crust [*Silver*, 1992] (Figure 1).

The Cuyamaca-Laguna Mountains shear zone (CLMSZ), a NW striking, NE dipping zone of ductile deformation, extending some 50 km along the boundary separating the eastern and western plutonic zones, is the focus of this paper (Figure 1) [*Silver et al.*, 1979; *Todd et al.*, 1988]. Prior investigators speculated that the 5 to 20-km-wide CLMSZ was an Early Cretaceous contractional structure [*Todd et al.*, 1988; *Bracchi et al.*, 1993; *Miller et al.,* 1993] which formed as a Late Jurassic/Early Cretaceous island arc (now represented by the Santiago Peak Volcanics and related western zone plutons), collided with, and accreted to the deposits of a basin (now represented by the Julian Schist and equivalents) fringing the western margin of North America [*Gastil et al.*, 1978, 1981; *Todd et al.*, 1988]. In this model the plutons of the CLMSZ are generated and deformed during Early Cretaceous collision at ~ 120 Ma to 105 Ma [*Todd et al.*, 1988].

Detailed mapping of two relatively well-exposed areas of the CLMSZ, in conjunction with reconnaissance work, suggests that the CLMSZ is a polygenetic structure (Figure 2). Early movements occurred during the interval of 118 to 115 Ma and record reverse sense displacements [*Bracchi*, 1993; *Thomson et al.*, 1994]. Younger deformation generated normal sense mylonites and is constrained to the interval of ~105 to 94 Ma [*Walawender et al.*, 1990, 1991; *G.H.Girty et al.*, 1994; *Miller,* 1994]. As an alternative to collision, we suggest that the western and eastern plutonic zones developed adjacent to each other in a transitional continental margin setting. Our model implies that structures in the CLMSZ are intra-arc and that the changing west to east geophysical, petrological and geochemical characteristics observed across the batholith are the product of the protracted development of a magmatic arc across a preexisting lithospheric join.

Cuyamaca-Laguna Mountains Shear Zone

Rock Types, Geochemistry, and Ages

Todd et al. [1988] described a variety of metamorphic and plutonic rocks within the CLMSZ (Figure 2). Our study focuses specifically on the informally recognized Harper Creek gneiss, Cuyamaca Reservoir gneiss, and Pine Valley granodiorite. Within the CLMSZ the Pine Valley granodiorite has been mapped as several discrete bodies (Figure 2). Most of these bodies display a moderately to weakly developed solid-state overprint with one exception, which is a well-developed protomylonite. In order to emphasize the relatively unique and mappable attributes of this body, we refer to it as the Oriflamme Canyon protomylonite (Figure 2) [*Bracchi*, 1993].

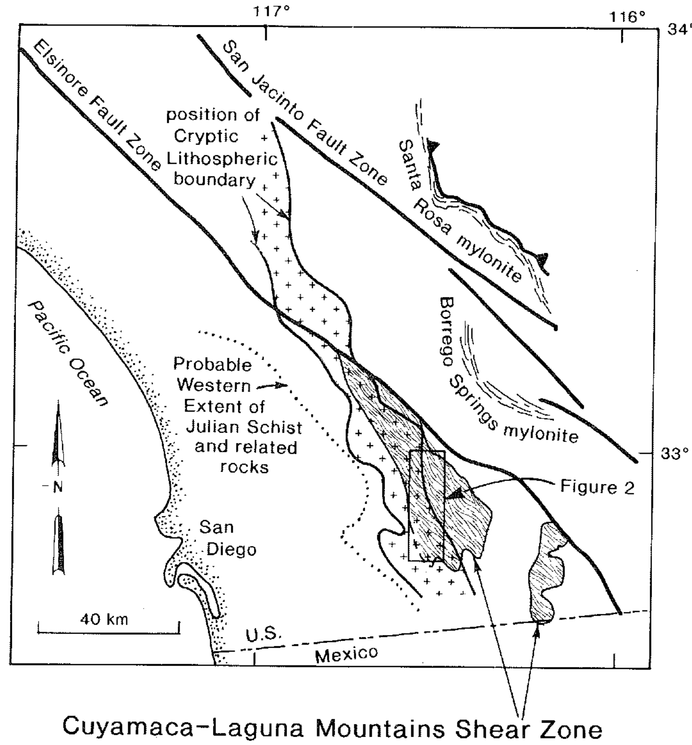

Figure 1. Location of the Cuyamaca-Laguna Mountains shear zone, Santa Rosa and Borrego Springs mylonite belts, major Neogene strike-slip faults, a hypothetical cryptic lithospheric boundary, and Figure 2 in southern California. Map is modified from *Todd et al.* [1988].

Harper Creek gneiss. The protolith of the Harper Creek gneiss is interpreted to be granodioritic but probably also included granite and tonalite [*Leeson*, 1989; *Miller et al.*, 1993; *Bracchi et al.*, 1993]. Accessory minerals are zircon, sphene, white mica, biotite, and, uncommonly, amphibole. Foliated and occasionally folded metasedimentary inclusions of the Julian Schist or correlative rocks are common within the Harper Creek gneiss (*Leeson*, 1989; *Bracchi*, 1993; *Girty et al.*, 1993). Trace element data cluster in the volcanic arc field on the Rb:Nb+Y granitoid discrimination plot of *Pearce et al.* [1984] (Figure 3a) [*Leeson*, 1989; *Bracchi et al.*, 1993; *Miller et al.*, 1993].

U/Pb zircon data from two different bodies of the Harper Creek gneiss yielded minimum ages of 156 $\pm$ 12 Ma (number of samples n =12 fractions) [*Girty et al.*, 1993] and 234 $\pm$ 39 Ma (n =7 fractions) [*Thomson*, 1994]. The younger age may have been derived from a piece of the adjacent Cuyamca Reservoir gneiss sheared off and incorporated into the Harper Creek gneiss during later mylonitization. Invariably, zircon samples collected from the Harper Creek and other gneissic rocks in the CLMSZ contain an inherited Precambrian Pb

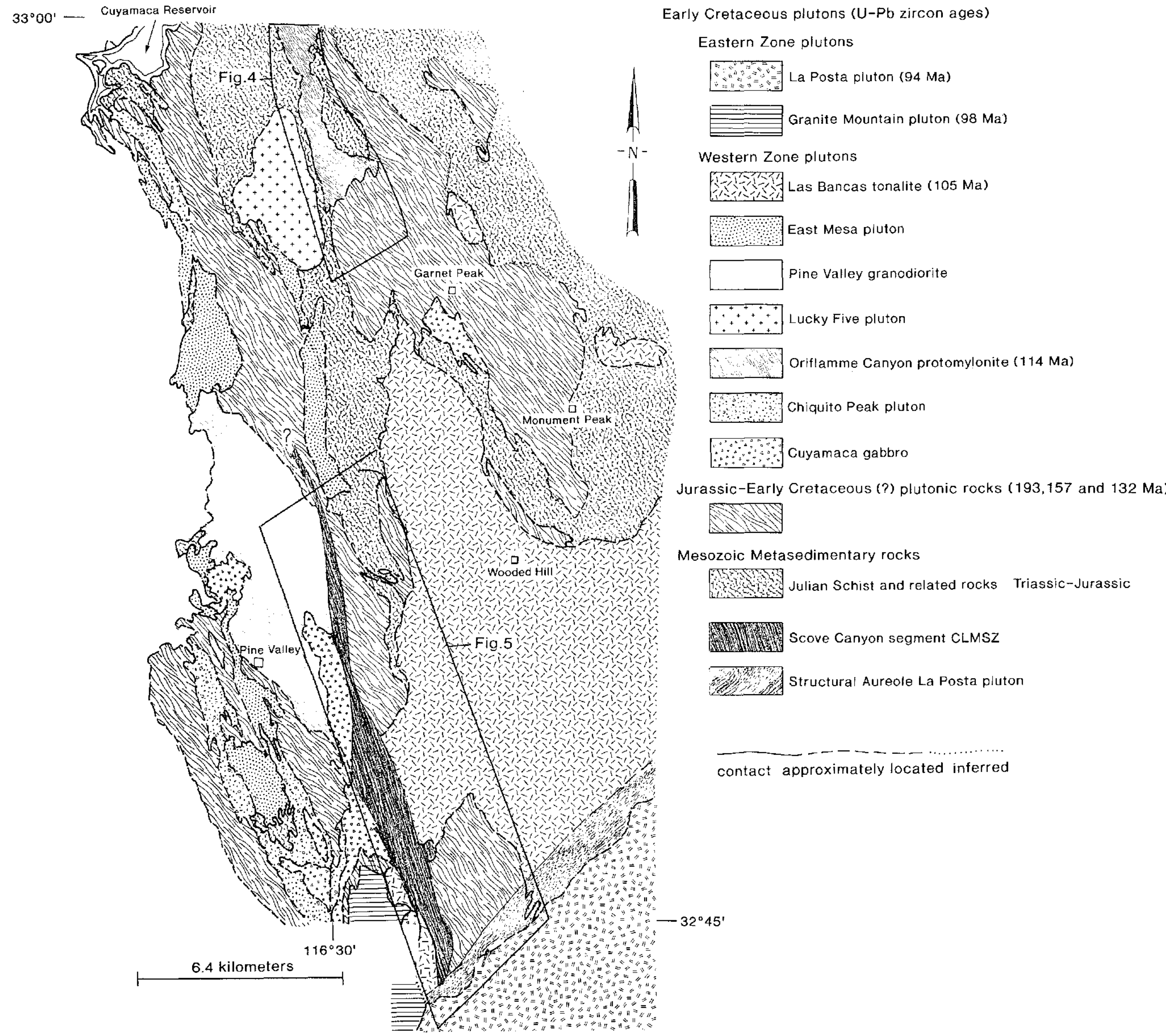

Figure 2. Geologic map of a portion of the Cuyamaca-Laguna Mountains shear zone showing locations of Figures 3 and 4. Map is modified from *Todd et al.* [1988].

component [e.g., *Leeson*, 1989; *Girty et al.*, 1993, *M.S. Girty et al.*, 1994; *Thomson*, 1994]. In addition, analyzed zircons probably were affected by high-temperature (*T*) mylonitization and Pb loss during emplacement of younger Early and Late Cretaceous plutonic rocks [*Thomson*, 1994]. This complicated, multistage history is responsible for the relatively large uncertainties associated with U/Pb zircon ages of the Harper Creek and related Triassic-Jurassic and Early Cretaceous gneisses of the CLMSZ [*M.S. Girty et al.*, 1994; *Thomson*, 1994].

Cuyamaca Reservoir gneiss. The protolith of the Cuyamaca Reservoir gneiss ranges from granodiorite to tonalite but is interpreted to have been predominantly granodioritic (*Leeson*, 1989; *Miller et al.*, 1993). Accessory minerals are biotite, sphene, zircon, amphibole, and, uncommonly, pyroxene. Elongated microgranitoid enclaves are locally abundant, whereas blocky, previously foliated and folded metasedimentary inclusions of the Julian Schist or related rocks are less common. Trace elements suggest that the Cuyamaca Reservoir gneiss was generated within a volcanic arc setting (Figure 3b) [*Miller et al.*, 1993; *Thomson et al.*, 1994]. Chondrite-normalized rare earth element (REE) patterns exhibit moderate light REE enrichment, moderate negative europium anomalies, and essentially flat, heavy REE [*Thomson*, 1994]. These patterns are like the western REE zone of the Peninsular Ranges batholith as defined by *Gromet and Silver* [1987]. However, REE in the Cuyamaca Reservoir gneiss are slightly more enriched in the light REE, a characteristic which may reflect assimilation of metasedimentary materials [*Thomson*, 1994]. U/Pb zircon work has yielded minimum Late Jurassic and Late Jurassic/Early Cretaceous ages of 161 ± 12 Ma (n = 4

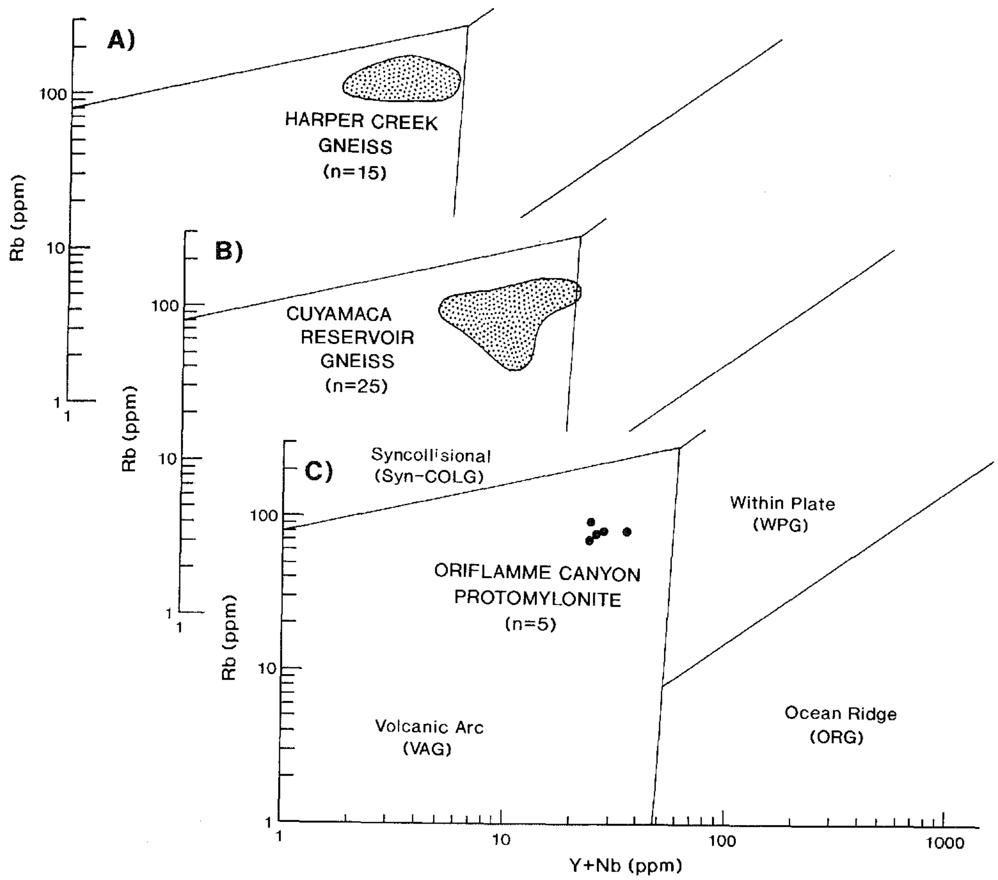

Figure 3. Trace element data fro (a) Harper Creek gneiss, (b) Cuyamaca-Reservoir gneiss, and (c) Oriflamme Canyon protomylonite, derived from X-ray fluorescence analyses of 45 samples, collected from throughout areas shown in Figures 4 and 5, plotted on the Rb versus Y+Nb discrimination diagram of *Pearce et al.* [1984]. Single 2:1 lithium tetraborate/rock powder fused disks were analyzed on an automatic Rigaku 3370 spectrometer at Washington State University, Pullman, Washington. Each element analysis was fully corrected for line interference and matrix effects. Repeated analysis of well-characterized standards suggests that precisions of plotted elements, as measured by 1 standard deviation values, are better than 4.0 relative percent. The tabulated results of plotted trace element analyses will be provided upon written request, free of charge, by the second author.

fractions) and 149 ± 12 Ma (n = 5 fractions) for the Cuyamaca Reservoir gneiss [*Thomson*, 1994].

Oriflamme Canyon protomylonite. The protolith of the Oriflamme Canyon protomylonite is interpreted to be a granodiorite, but it also included tonalite and quartz diorite [*Bracchi*, 1993]. Accessory minerals are biotite, amphibole, sphene, and zircon. Locally, microgranitoid enclaves are present. Trace element data indicate emplacement in a volcanic arc setting (Figure 3c) [*Bracchi et al.*, 1993]. A single sample from the Oriflamme Canyon protomylonite yielded a U/Pb zircon age of 115 ± 2 Ma (n = 4 fractions) (Figure 3) [*Bracchi*, 1993; *Thomson*, 1994].

Pine Valley granodiorite. The Pine Valley granodiorite ranges from granite to tonalite but is predominantly granodioritic in composition [*Miller et al.*, 1993]. Accessory minerals include zircon, biotite, sphene, and minor amphibole. Published geochemical data suggest that the Pine Valley granodiorite was emplaced in a volcanic arc setting [*Carrollo and Walawender*, 1993]. Concordant U/Pb zircon data indicate an age of ~118 Ma [*Walawender et al.*, 1991]. This age is in general agreement with a U/Pb zircon age cited by *Todd et al.* [1988] for the same body. No analytical uncertainties were provided by *Todd et al.* [1988] or *Walawender et al.* [1991].

Evidence For D_1 Deformation

The oldest ductile fabrics (D_1) are the result of NE-SW contraction in a relatively high-temperature environment (~500° C), as indicated by the ubiquitous occurrence of strain-induced myrmekite and the dynamic partial recrystallization of plagioclase [*Simpson*, 1985; *Simpson and De Paor*, 1991]. D_1 produced S_1, a pervasively developed mylonitic gneissosity, in the Triassic-Jurassic Harper Creek and Cuyamaca Reservoir gneisses (Figures 4 and 5). In contrast, S_1 in the ~115 Ma Oriflamme Canyon protomylonite and ~118 Ma Pine Valley granodiorite is a well-developed protomylonitic foliation in the former unit and a weakly to moderately developed solid-

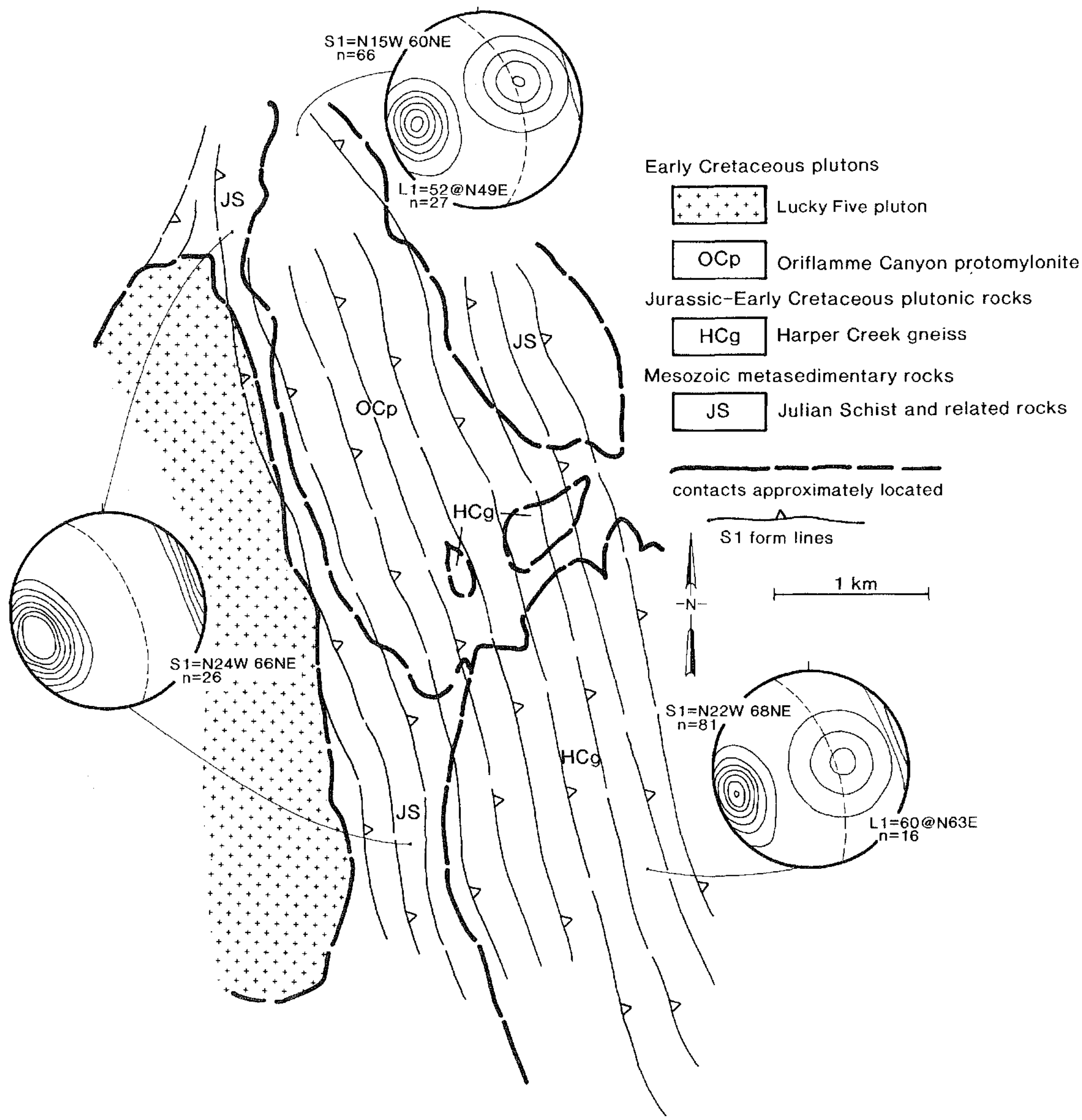

Figure 4. Geologic map showing the distribution and orientations of D_1 structures in the Harper Creek gneiss, Oriflamme Canyon protomylonite, and Julian Schist in a moderately exposed area of the Cuyamaca-Laguna Mountains shear zone. See Figure 2 for location. Accompanying fabric diagrams are poles to S_1 and/or L_1 attitudes plotted and contoured on lower hemisphere equal area stereonets. Density contours are based on the method of *Robin and Jowett* [1986] as used in the program SpheriStat of *Pangaea Scientific* [1992], and are given in 6-sigma intervals.

state foliation in the latter pluton. Since D_1 structures are more intensely developed in the older units, we first describe the characteristics of D_1 structures for the Triassic-Jurassic gneisses and then for the younger, ~115 and ~118 Ma, plutons.

Triasssic-Jurassic Plutonic Rocks

The Harper Creek and Cuyamaca Reservoir gneisses commonly exhibit a penetrative NW striking, NE dipping mylonitic gneissosity (S_1) (Figures 4 and 5). The pervasive development of S_1 resulted in the obliteration of nearly all traces of textures associated with the early magmatic history of the Harper Creek and Cuyamaca Reservoir gneisses (*Bracchi*, 1993). However, locally preserved, only partially reconstituted hypidiomorphic-granular granitoid textures and magmatic foliation defined by aligned euhedral/subhedral plagioclase, attest to the magmatic origin of these rocks.

S_1 is characterized by alternating platy to highly elongated domains (~0.5-0.25 mm thick) composed of varying proportions of quartz + K-feldspar + plagioclase + biotite ± hornblende ± white mica. In these domains, dynamically recrystallized polycrystalline quartz ribbons and lenses the elongation direction of partially recrystallized plagioclase and K-feldspar, and the [001] faces of biotite and white mica are aligned parallel to S_1 within the Harper Creek gneiss. S_1 is defined in a similar fashion within the Cuyamaca Reservoir gneiss, but aligned, partially recrystallized hornblende is commonly present, whereas white mica is absent. Myrmekite colonies, developed on crystal edges facing the inferred maximum shortening direction of elongated K-feldspar porphyroclasts, are common in both units [cf. *Simpson*, 1985].

Lying in the plane of S_1, in both the Harper Creek gneiss and Cuyamaca Reservoir gneisses, is a locally well-developed stretching lineation (L_1) (Figures 4 and 5). L_1, consistently plunging steeply to the NE, is defined by elongated quartzofeldspathic and/or quartzomicaceous aggregates.

Late Early Cretaceous Plutonic Rocks

In the Oriflamme Canyon protomylonite and the Pine Valley granodiorite, S_1 is defined by the aligned [001] facies of euhedral/subhedral biotite and the aligned, long dimensions of (1) dynamically recrystallized quartz lenses or ribbons, (2) polysynthetically twinned, occasionally concentrically zoned and fractured, euhedral to subhedral plagioclase, and (3) minor subhedral amphibole. K-feldspar is flattened and variably elongated within S_1, particularly in samples from the Oriflamme Canyon protomylonite, and commonly displays moderately to well-developed myrmekite colonies on crystal facies oriented orthogonally to the inferred maximum shortening direction.

Steeply to moderately NE plunging stretching lineations L_1 defined by elongated quartzofeldspathic and/or quartzomicaceous aggregates are well developed in the Oriflamme Canyon protomylonite but are absent to weakly developed in the Pine Valley granodiorite (Figures 4 and 5). In XZ sections, viewed looking to the north, shear bands (C_1) dipping ~25°NE strike parallel to S_1 and deflect it in a sinistral (reverse) sense in the Oriflamme Canyon protomylonite but have not been recognized in the Pine Valley granodiorite. New and subgrain development in quartz, plagioclase, and K-feldspar is evident along C_1 surfaces. Using the criteria of *Paterson et al.* [1989], microstructures described in this and the preceding paragraph are characteristic of magmatic foliation which, with decreasing temperatures, pass progressively into solid-state protomylonitic deformation [*Gapais*, 1989].

Timing and Kinematic Significance of D_1

D_1 structures transect Triassic-Jurassic orthogneisses and late Early Cretaceous plutonic rocks as young as 115 ± 2 Ma (i.e., the Oriflamme Canyon protomylonite) but do not occur in the Las Bancas tonalite which has a concordant U/Pb zircon age of ~105 Ma (Figures 4 and 5) [*Walawender et al.*, 1991]. The fact that S_1 can be traced directly from the Harper Creek gneiss into the Oriflamme Canyon protomylonite and adjacent Julian Schist suggests that foliation development was coeval (Figure 4). The orientation of S_1, L_1 and locally well-developed reverse sense shear bands (C_1) within the Oriflamme Canyon protomylonite and the Julian Schist indicate that these structures formed as the result of NE-SW contraction (Figure 4) [*Bracchi et al.*, 1993]. The qualitative observation that the Julian Schist and Triassic-Jurassic orthogneisses are more highly strained and reconstituted than late Early Cretaceous plutonic rocks suggests that the late Early Cretaceous plutons were emplaced during the waning stages of D_1 deformation and are thus late syntectonic intrusives.

Davis and Gastil [1993] obtained a Rb/Sr age of 117 ± 8 Ma for an amphibolite grade sample of the Julian Schist collected from the type locality ~ 20 km to the NE of Figure 2. Through reconnaissance work, in conjunction with the excellent mapping of *Germinario* [1993], we have been able to trace D_1 structures into the area sampled by *Davis and Gastil* [1993]. *Germinario* [1993] observed no evidence for multiple phases of metamorphism or deformation, and as a result, the reported Rb/Sr data are interpreted as an estimate of the age of metamorphism associated with D_1 [R.G. Gastil, personal communication, 1994]. Such an interpretation is consistent with 115 and 122 Ma replicate K-Ar biotite ages for a syntectonic pluton mapped by *Todd et al.* [1988] within the CLMSZ. Thus relationships outlined in this and preceding paragraphs imply that D_1 probably began some unknown time prior to the syntectonic emplacement of the ~118 Ma Pine Valley granodiorite and the 115 ± 2 Ma Oriflamme Canyon protomylonite, that it was active at ~117 ± 8 Ma, and that it was over by ~105 Ma, the age of the oldest Early Cretaceous pluton not affected by D_1 (i.e., the Las Bancas pluton) (Figure 5).

Evidence For D_2 Deformation

Scove Canyon Segment of the CLMSZ

A continuous normal sense shear zone, herein after referred to as the Scove Canyon segment, has been traced for over 12 km along the western half of the CLMSZ (Figures 2 and 6). S-C mylonites defining the Scove Canyon segment transect D_1 structures in the Harper Creek and Cuyamaca Reservoir gneisses and can be traced through portions of the ~105 Ma Las Bancas tonalite, ~118 Ma Pine Valley granodiorite, and the undated Cuyamaca Peak gabbro (Figures 2 and 6). Within the Scove Canyon segment, NW striking and NE dipping platy mylonitic foliation (S_2) is pervasive and penetrative (Figure 6). Typically, S_2 is defined by the alignment of dynamically recrystallized quartz ribbons, the long dimensions of partially recrystallized plagioclase and K-feldspar, and the [001] facies of biotite and white mica. Myrmekite colonies locally are well developed along the edges of K-feldspar porphyroclasts facing the inferred maximum contraction direction, and along with the partial recrystallization of plagioclase they indicate relatively high temperatures (~500°C) of deformation [*Simpson*, 1985; *Simpson and De Paor,* 1991]. NE plunging stretching lineations (L_2) lie in the plane of S_2 and are defined by elongated quartzofeldspathic and/or quartzomicaceous aggregates (Figure 6).

Shear bands (C_2) strike subparallel to S_2 but dip more steeply (~84°) to the NE and are surfaces along which significant grain-size reduction has occurred. In thin sections, normal sense shear is demonstrated by dextral deflections of S_2 as they enter and leave C_2 domains. Other dextral sense indicators include retort feldspar porphyroclasts, fractured and offset feldspar porphyroclasts, and locally developed grain shape preferred orientation in quartz ribbons.

As the Scove Canyon segment and S_1 in the older Triassic-Jurassic orthogneisses are traced to the southeast, they are dextrally deflected, in map view, into the ~N40°E striking, subvertical, ~1-km wide structural aureole of the Late Cretaceous La Posta pluton (Figures 2 and 6). The structural aureole is well developed in the Cuyamaca Reservoir gneiss and the Las Bancas tonalite (Figures 2 and 6). Along the northwestern margin of the aureole, deflected S_1 and S_2 take on a coarsened and more enhanced gneissic character, and a locally developed new mylonitic foliation (S_3) is defined by ~20-cm-wide zones of pronounced grain size reduction. Distinguishing S_1 from S_2 or S_3 is difficult in the interior of the structural aureole due to progressive rotation of all planar fabric elements into a parallel northeastward orientation. Thus in the main part of the aureole the foliation (S_T) is a composite of S_1, S_2, and S_3 (Figure 6). Dynamically recrystallized, highly elongated, and flattened quartz, plagioclase, and K-feldspar crystals displaying well-developed, strain-induced myrmekite colonies are characteristic of S_T.

Lying in the plane of S_T is a pronounced stretching lineation (L_T) defined by elongated quartzofeldspathic and quartzomicaceous aggregates. L_T plunges steeply to the northeast, clustering around an attitude of 71° at N37°E (Figure 6).

A complicated array of crenulations, shear bands, and apparent strike-slip faults with 5 to 20-cm displacements are spatially restricted to the structural aureole of the La Posta pluton where they affect S_T to variable degrees. Although not well understood at this time, they probably are the result of a complex heterogeneous strain field associated with the development of the aureole.

D2 Structures Outside the Scove Canyon Segment

Normal sense shear bands crosscutting D_1 structures are not pervasively developed in the CLMSZ outside the Scove Canyon segment. When present, grain size reduction is evident along the shear bands, and the bands typically cut S_1 at a small angle in strike-oriented sections and dip 87° - 89° to the NE. Normal sense shear bands outside the Scove Canyon segment are geometrically, texturally, and mineralogically similar to those observed in the Scove Canyon segment. On the basis of these similarities and the temporal relationship between the normal sense shear bands and S_1 described above, we infer that the normal sense shear bands outside of the Scove Canyon segment formed during D_2. Hence D_2 structures representing NE-SW extension are apparently widespread but are domainally developed within the CLMSZ.

Timing of D2

The Scove Canyon segment crosses the ~105 Ma Las Bancas tonalite and is, in turn, deflected by the structural aureole of the La Posta pluton (Figure 6). *Walawender et al.* [1990] reported a U/Pb zircon age of 94 ± 2 Ma for the latter body (Figure 6). Hence the Scove Canyon segment and, by inference, normal sense shear bands outside the Scove Canyon segment, formed sometime between ~105 and ~94 Ma.

Discussion And Conclusions

Triassic-Jurassic plutons in the CLMSZ intruded and partially incorporated metasedimentary rocks that are correlated to the Julian Schist. This relationship implies that the Julian Schist and related rocks can be no younger than the age of the oldest pluton which intrudes or engulfs them (i.e., the Triassic-Early Jurassic (234 ± 39 Ma) Harper Creek gneiss), an interpretation that is consistent with a Triassic fossil collected from the Julian Schist [*Gastil et al.*, 1978; *Todd et al.*, 1988]. Using the Decade of North American Geology timescale [*Palmer*, 1983] and given the uncertainties in the U-Pb data for the Harper Creek gneiss, portions of the Julian Schist and related rocks may be as young as Early Jurassic.

Rare earth element and detrital zircon studies show that the Julian Schist and related rocks are composed of, at least in part, continental detritus [*Schar*, 1993; *Gastil and Girty*, 1993], whereas scattered occurrences of orthoamphibolite layers, blocks, and lenses suggest a syndepositional volcanic component [*Todd et al.*, 1988]. *Germinario* [1993] interpreted the Julian Schist to have been deposited in a deep marine-submarine fan environment. *Saleeby and Busby-Spera* [1992] suggested a transtensional continental margin forearc setting associated with the regionally developed extensional Triassic-Jurassic arc of *Busby-Spera* [1988].

Geochemical data derived from transects across the western and eastern plutonic zones of the Peninsular Ranges batholith suggest that the batholith developed in a poorly understood lithospheric setting that involved oceanic crust on the west and a sialic crustal component on the east [*De Paolo*, 1981; *Ague and Brimhall*, 1987, 1988; *Gromet and Silver*, 1988; *Todd et al.*, 1988; *Silver*, 1992). The boundary separating these two contrasting crustal components is marked by a broad band of geophysical, geochemical, and petrological discontinuities that have been discussed in some detail by *Gromet and Silver* [1987] and *Todd et al.* [1988]. The band of discontinuities marks the cryptic join between oceanic and continental lithosphere (Figure 1). In the arc-continent collisional model the proposed suture zone lies to the west of the band of discontinuities described above and is nowhere exposed. However, there is no evidence for accreted ocean basin sediments or oceanic crust along the proposed suture, and as a result, we view it as an unlikely candidate for an arc-continent collisional suture (Figure 1). In contrast, the Julian Schist crops out on opposite sides of the band of discontinuities defining the cryptic crustal join. Hence we view the Julian Schist as an overlap sequence. If such an interpretation is correct, then the Triassic-Jurassic and Early Cretaceous plutons of the CLMSZ were emplaced into the sedimentary fill of a composite forearc basin which was probably floored by highly extended continental crust on the east and oceanic crust on the west [e.g. *Dickinson and Seeley,* 1979].

Geochemical arguments suggest that the Triassic-Jurassic and Early Cretaceous plutons of the CLMSZ were derived from I type magmas variably contaminated by assimilation of sialic or reduced pelitic material (Figure 3) [e.g. *White et al.*, 1986; *Ague and Brimhall*, 1987, 1988; *Bracchi et al.*, 1993; *Miller et al.*, 1993; *Thomson et al.*, 1994]. In addition, zircons collected from plutons of the CLMSZ [*M.S. Girty et al.*, 1994; *Thomson*, 1994] and from the Santiago Peak Volcanics [*Meeth*, 1993; *Kimbrough and Herzig*, 1994] commonly contain an inherited Precambrian Pb component. Thus geochemical and geochronological data are consistent with the Triassic-Jurassic and Early Cretaceous plutons in the CLMSZ and the Santiago Peak Volcanics being generated in a continental margin arc setting which supplanted deposition of the Julian

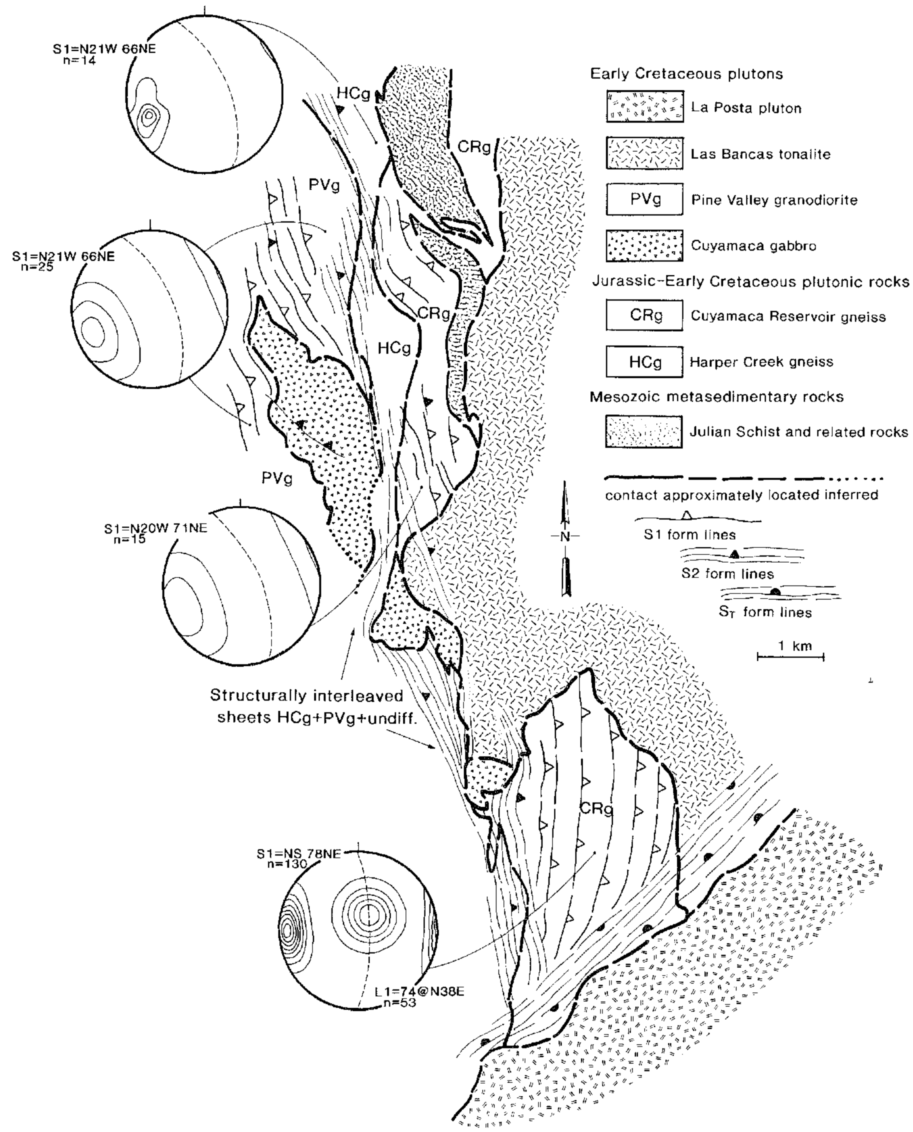

Figure 5. Geologic map showing the distribution and orientations of D1 structures in the Cuyamaca Reservoir gneiss, Harper Creek gneiss, and Pine Valley granodiorite in a moderately to locally well-exposed area of the Cuyamaca-Laguna Mountains shear zone. See Figure 2 for location. Accompanying fabric diagrams are poles to S_1 and/or L_1 attitudes plotted and contoured on lower hemisphere equal-area stereonets. Density contours are based on the method of *Robin and Jowett* [1986] as used in the program SpheriStat of *Pangaea Scientific* [1992], and are given in 6-sigma intervals.

Schist and related rocks in a transtensional forearc environment [*Saleeby and Busby-Spera* 1992].

During the Late Jurassic, ~160 to ~144 Ma, the Farallon and North American plates were converging in an oblique sinistral fashion [*Engebretson et al.*, 1985; *Glazner*, 1991]. Earlier movements during the Early and Middle Jurassic are not well known, but geological relationships along the Cordilleran margin suggest a dextral oblique convergence pattern [*Saleeby and Busby-Spera*, 1992; *Saleeby and Busby*, 1993). Although existing U/Pb zircon data do not uniquely constrain the timing of the earliest phase of plutonism in the CLMSZ, they do suggest that plutonism may have begun as early as the Triassic (e.g., 234 ± 39 Ma), whereas later magmatism probably occurred in the Late Jurassic around 160 ± 12 Ma [*Thomson*, 1994]. Therefore it is possible that the Triassic-Jurassic plutons of the CLMSZ were emplaced into a continental margin undergoing oblique dextral shear during the Early and Middle Jurassic, followed by oblique sinistral shear in the Late Jurassic and Early Cretaceous [*Engebretson et al.*, 1985; *Glazner*, 1991;*Saleeby and Busby-Spera*, 1992; *Saleeby and Busby*, 1993].

By the Early Cretaceous, ~125 to ~115 Ma, convergence between the North American and Farallon plates was nearly orthogonal [*Engebretson et al.*, 1985]. Arc-perpendicular NE-SW contractional deformation (D_1), metamorphism, and Early Cretaceous syntectonic emplacement of the Pine Valley granodiorite and Oriflamme Canyon protomylonite within the CLMSZ occurred during the interval ~118 to ~115 Ma, which

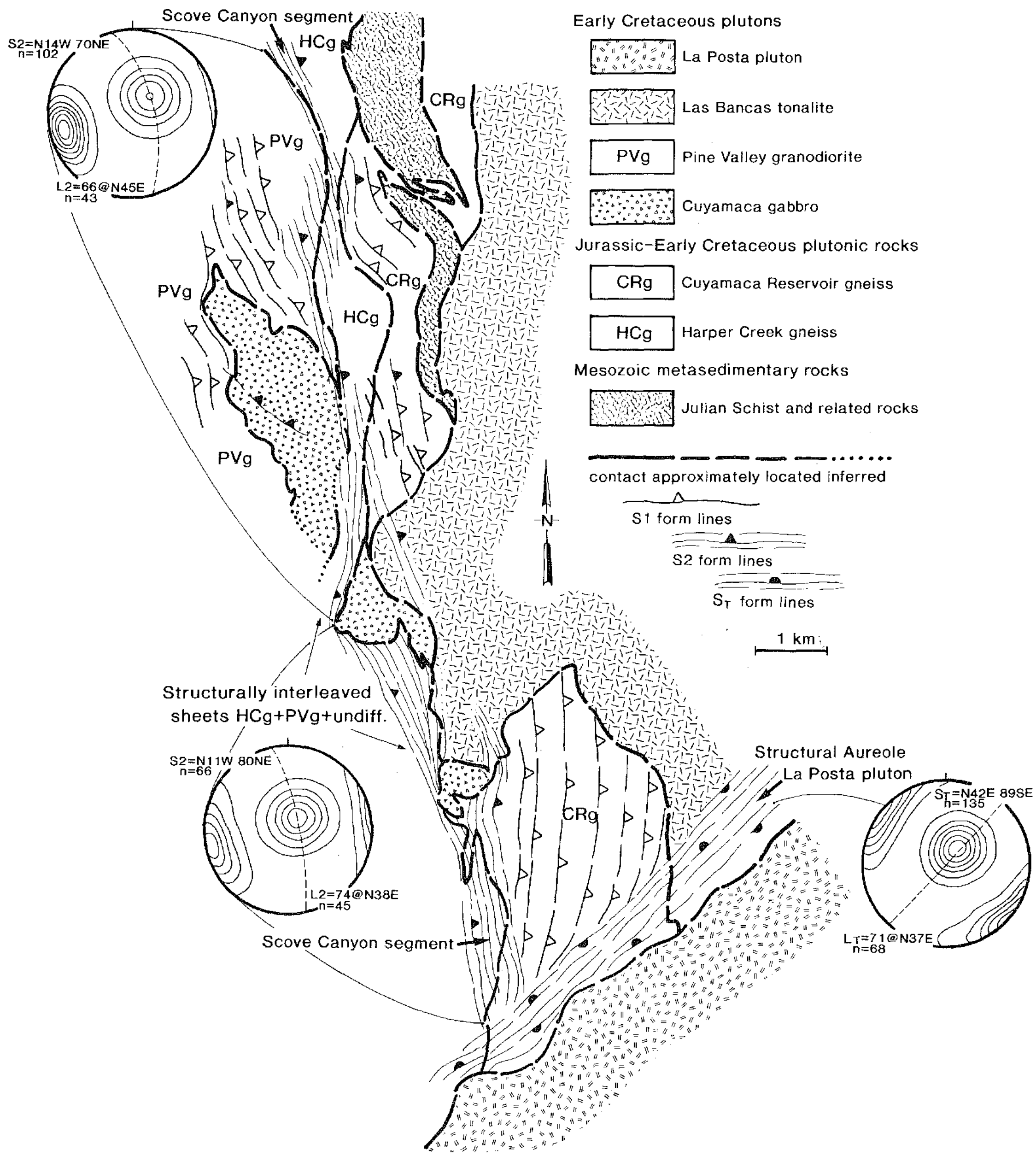

Figure 6. Geologic map showing the distribution and orientations of D_2 structures in the Scove Canyon segment of the Cuyamaca-Laguna Mountains shear zone. See Figure 1 for location. Accompanying fabric diagrams are poles to S_2 and S_T, and L_2 and the L_2 and L_T attitudes plotted and contoured on lower hemisphere equal area stereonets. Density contours are based on the method of *Robin and Jowett* [1986] as used in the program SpheriStat of *Pangaea Scientific* [1992], and are give in 6-sigma intervals.

coincides with this period of normal convergence and associated "vigorous" subduction [e.g., *Glazner,* 1991]. The similarity in timing of deformation, metamorphism, plutonism, and normal convergence is either coincidence, or it suggests that these features are somehow related. Although not understood in detail, one possible explanation is that the mechanically weak, thermally and melt-softened cryptic interface between oceanic and continental lithosphere yielded during the normal convergence event, resulting in the concentration of strain into the CLMSZ. In such a scenario, syntectonic arc magma emplaced into the CLMSZ acts to focus deformation and metamorphism into a highly strained belt [e.g., *Hollister and Crawford,* 1986; *Tobisch et al.,* 1989; *Collins et al.,* 1991; *Sandiford et al.,* 1992]. Older plutonic and metamorphic rocks within the CLMSZ are intensely reworked during contraction, and evidence for earlier phases of deformation associated with intra-arc transpression or transtension, if any existed, is largely obliterated during the Early Cretaceous contractional event, ~125 - 115 Ma.

Following the normal convergence event, movement between the North American and Farallon plates became oblique and dextral in character [*Engebretson et al.*, 1985]. NE-SW, approximately arc-perpendicular D_2 extension occurred within the CLMSZ during this period as magmatism migrated from the western to the eastern plutonic zone [*Silver et al.*, 1979; *Silver and Chappell*, 1988; *Walawender et al.*, 1990, 1991]. Mechanisms which account for the extensional deformation are poorly understood: however, two possibilities are proposed, gravitational collapse and structural loading.

Extension in the CLMSZ may represent the creation and failure of an unstable and overthickened regionally developed crustal/magmatic welt which, others have argued probably covered much of the SW Cordillera [e.g., *Livaccari*, 1991; *Gastil et al.*, 1992; *George and Dokka*, 1994, and references therein]. In general, the central theme of the extensional collapse model is that crustal thickening during the Cretaceous is the result of a combination of compressive plate-convergence forces and arc magmatism [*Livaccari*, 1991; *Gastil et al.*, 1992; *George and Dokka*, 1994). Gravitationally induced extensional collapse is thought to have occurred as a result of a decrease in arc-perpendicular plate boundary forces induced by a change in plate convergence directions or rates, coupled with a decrease in the thermally and melt-softened strength of overthickened crust [e.g., *Livaccari*, 1991]. Extensional collapse may have begun as early as the Late Cretaceous [*George and Dokka*, 1994], but some authors view it as a largely Tertiary event [*Coney and Harms*, 1984; *Livaccari*, 1991; *Gastil et al.*, 1992].

Recently completed fission track and structural work indicate that the Santa Rosa mylonite belt of the eastern Peninsular Ranges mylonite zone was affected by a major phase of synplutonic NE-SW contraction, ~ 99 to ~94 Ma, followed and possibly overlapped by a phase of synplutonic, approximately NE-SW extension between ~94 and ~92 Ma (Figure 1) [*Erskine and Wenk*, 1985; *George and Dokka*, 1994]. *George and Dokka* [1994] hypothesized that the Santa Rosa and Borrego Springs mylonite belts are the along-strike equivalents of the CLMSZ offset ~54 km in a dextral manner along the Elsinore and San Jacinto faults, which display 30 km and 24 km of displacement, respectively. However, contraction in the SW portions of the CLMSZ that we have studied predates contraction in the Santa Rosa and Borrego Springs mylonite belts by ~15 to 30 m.y. In addition, the CLMSZ developed along the boundary between the western and eastern plutonic zones, whereas the Santa Rosa and Borrego Springs mylonite belts occur entirely within the eastern plutonic zone, indicating that the CLMSZ developed in a more outboard setting (Figure 1).

Prior investigators suggested that ~10 to ~100 km of NW displacement of the hanging wall block of the Santa Rosa and Borrego Springs mylonite belts may have occurred during ~99 - 94 Ma contraction [*Todd et al.*, 1988, and references therein]. The probable along-strike equivalents of the Santa Rosa and Borrego Springs mylonite belts are described by *Grove* [1989]. Extension in the CLMSZ occurred during this interval, ~105 and 94 Ma, suggesting that D_2 may represent an extensional readjustment of the CLMSZ as it was vertically loaded by the hanging wall block of the Santa Rosa and Borrego Springs mylonite belts.

In conclusion, although some data presented in this paper do not preclude the arc-continent collisional model of *Gastil et al.* [1978] and *Todd et al.* [1988], we think that the close temporal and spatial relationships between deformation, metamorphism, and arc magmatism argue against such an interpretation, and thus leave room for consideration of alternative hypotheses such as the one presented in the preceding paragraphs. In addition, we believe that the Peninsular Ranges batholith is not unique, as far as batholiths go, and argue that it probably was constructed in a manner analogous to the Cretaceous-aged Sierra Nevada batholith, where arc magmatism and intra-arc deformation sometimes played significant and complexly interrelated roles [e.g., *Saleeby and Busby-Spera*, 1992, *Saleeby and Busby*, 1993; *Tobisch et al.*, 1989, 1993].

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