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THE SAN ANDREAS FAULT SYSTEM IN THE VICINITY OF THE CENTRAL TRANSVERSE RANGES PROVINCE, SOUTHERN CALIFORNIA

By

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SUMMARY

The vicinity of the central Transverse Ranges is a structurally complex region that is traversed by several major fault zones. The Banning, San Jacinto, and San Andreas faults are right-lateral strike-slip faults of the San Andreas transform system. The San Gorgonio Pass and Cucamonga fault zones are compressional thrust- and reverse-fault complexes. The Crafton Hills horst-and-graben complex, the Tokay Hill and Peters faults in the Cajon Pass region, and the Beaumont Plain fault complex are extensional fault zones. The compressional and extensional fault complexes owe their origin and kinematics to complications within the San Andreas transform fault system.

The Banning fault has had a complex history that includes both left- and right-lateral displacements. During middle Miocene time the ancestral Banning fault zone may have generated left-lateral displacements that juxtaposed the Peninsular Ranges block against the San Gabriel Mountains block along a regionally extensive fault system that included the Malibu Coast-Santa Monica fault. During late Miocene time the Banning fault was incorporated into the San Andreas transform system and generated 16 to 25 km of right-lateral displacement; during this period the Banning probably was the eastward continuation of the San Gabriel fault in the San Gabriel Mountains. The Banning fault was abandoned by the San Andreas system in earliest Pliocene time. In San Gorgonio Pass the Banning fault has been obscured and reactivated by low-angle Quaternary faulting of the San Gorgonio Pass fault zone. In the Coachella Valley the Banning fault has been reactivated by Quaternary strike-slip faulting related to the San Andreas fault, and has generated about 3 km of right-lateral displacement that largely has been absorbed by convergence within the San Gorgonio Pass fault zone.

The San Andreas fault in the vicinity of the central Transverse Ranges consists of three segments--the Mojave Desert, Coachella Valley, and San Bernardino Mountains segments. The complex San Bernardino Mountains segment consists of multiple strands that had sequential movement histories. To the northwest and southeast these strands merge to form the simpler Mojave Desert and Coachella Valley segments.

The San Bernardino Mountains segment of the San Andreas fault consists of three paleotectonic strands (the Wilson Creek, Mission Creek, and Mill Creek faults) and a neotectonic strand (the San Bernardino strand). Together, these four strands have generated about 160 km of right-lateral displacement and record the total history of the San Andreas fault (*sensu stricto*) since its inception 4 or 5 m.y. ago. The Wilson Creek and Mission Creek faults together generated about 130 km of right-lateral displacement during Pliocene and Pleistocene time. The Wilson Creek fault, the older strand, generated about 40 km of displacement before it was deformed into a sinuous trace in the vicinity of the San Bernardino Mountains; this displacement estimate is based on our proposal that the Wilson Creek fault is the offset continuation of the Punchbowl fault in the San Gabriel Mountains--a structure that has about 40 km of right slip documented by other workers. In Pliocene time the Wilson Creek strand was succeeded by the Mission Creek strand, which generated the balance of the 130-km displacement before it was deformed and abandoned in late Pleistocene time. The Mill Creek strand subsequently evolved inboard (east) of the locked-up Mission Creek fault and generated about 8 km of right-slip during late Pleistocene time. Ultimately, the Mill Creek strand was abandoned as right-lateral activity shifted to the southwest front of the San Bernardino Mountains, where the neotectonic San Bernardino strand developed. The San Bernardino strand is aligned with the Coachella Valley segment of the Banning fault, but these two neotectonic right-lateral faults are separated by the San Gorgonio Pass fault zone and it is not clear that they ever formed a single throughgoing trace between the Coachella and San Bernardino valleys.

Two compressional fault complexes and an extensional fault system have evolved in the vicinity of the south-central Transverse Ranges in association with the San Andreas fault. The San Gorgonio Pass and Cucamonga fault zones consist of late Quaternary thrust and reverse faults that have evolved where neotectonic strands of the San Andreas and San Jacinto faults interact with the southeastern San Bernardino Mountains and San Gabriel Mountains, respectively. Northwest of the San Gorgonio Pass fault zone, crustal extension in the San Bernardino valley and vicinity has created normal dip-slip fault complexes like the Beaumont Plain fault zone, the Crafton Hills horst-and-graben complex, and the Tokay Hill and Peters faults in the Cajon Pass region.

The Quaternary tectonic framework of the central Transverse Ranges can be viewed as a regionally integrated response to an evolving left step in the San Andreas transform-fault system. The left step was initiated during Pleistocene time, and was accompanied by left-slip on the Pinto Mountain fault that gradually projected the San Bernardino Mountains westward across the path of the Mission Creek strand of the San Andreas fault and offset the Coachella Valley and Mojave Desert segments of the fault. The modern San Andreas fault has adjusted to this inherited left step, and various neotectonic fault complexes in the vicinity of the central Transverse Ranges have evolved in response to this adjustment. During latest Quaternary time, right-slip on the San Andreas fault has stepped left from the Coachella Valley segment to the Banning fault and thence into San Gorgonio Pass, where right-slip is absorbed by convergence within the San Gorgonio Pass fault zone. Some slip may step farther west onto the San Jacinto fault, where accelerated right-slip may have contributed to subsidence of the San Jacinto graben. Ultimately, slip steps back from the San Jacinto fault to the modern San Andreas fault, giving rise to the San Bernardino strand by reactivation of the Mission Creek fault. This right step has created a right-lateral shear couple and extensional strain field in the greater San Bernardino valley, with extension giving rise to normal dip-slip faults like those in the Crafton Hills horst-and-graben complex and the Tokay Hill and Peters faults.

INTRODUCTION

In this report we describe the tectonic framework and geologic history of faults in the vicinity of the central Transverse Ranges, southern California (fig. 1). The fault zones discussed include right-lateral faults of the San Andreas transform system (including the San Andreas fault itself), associated reverse and thrust faults in the vicinity of San Gorgonio Pass and the southeastern San Gabriel Mountains, and associated normal faults that occur between the San Jacinto and San Andreas faults in the vicinity of the San

Bernardino valley. The San Andreas fault has received much attention because it has played such an important role in the geological history of southern California. However, associated contractional and extensional fault zones have not been studied as thoroughly, even though they play important roles in the geologic framework and history of the central Transverse Ranges.

This review of paleotectonic and neotectonic fault complexes provides a geologic framework for studies of regional seismicity, earthquake potential, and earthquake hazards, and for our ongoing reconstruction of strike-slip displacements on faults of the San Andreas transform system. Our purpose is fourfold: (1) to describe various right-lateral strands of the San Andreas fault zone in the vicinity of the central Transverse Ranges; (2) to outline the geologic history of these strands; (3) to identify fault zones that are not part of the San Andreas zone but that have interacted with it in the context of the overall transform-fault system; and (4) to present a model that relates modern faults of the central Transverse Ranges within a coherent regional framework.

This study is a status report that updates a similar study released in 1985 as U.S. Geological Survey Open-File Report 85-365 (Matti and others, 1985). The update reflects ongoing geological studies conducted under the auspices of two U.S. Geological Survey programs--the National Geologic Mapping Program (GEOMAP and COGEOMAP Components) and the National Earthquake Hazards Reduction Program (Regional Geologic Hazards Element). This status report is the result of geologic-mapping investigations that are delineating the geologic framework of various fault complexes (Morton, 1978a,b,c; Morton and Matti, 1990a,b; Matti and others, 1992) and topical investigations that address the geologic history and strain budget of these fault complexes (Matti and others, 1982b; Morton and Matti, 1987; Harden and Matti, 1989; Morton and Matti, in press; Matti and Morton, in press).

MAJOR STRUCTURAL BLOCKS

The diverse basement terranes of southwestern California can be grouped into rocks of Peninsular Ranges-type, San Gabriel Mountains-type, and San Bernardino Mountains-type (fig. 2).

Basement rocks of ***San Gabriel Mountains-type*** (fig. 2A) consist of two crustal layers separated by a low-angle tectonic contact--the Vincent thrust (Ehlig, 1982). The upper thrust plate consists of Mesozoic plutons of various compositions, ages, and deformational styles that have intruded prebatholithic crystalline rocks. One distinctive Mesozoic granitoid unit is the Lowe pluton of Triassic age (Joseph and others, 1982a). The prebatholithic rocks largely are Proterozoic, and include orthogneisses and the anorthosite-syenite complex that is so well known from the western San Gabriel Mountains (Silver, 1971; Ehlig, 1981; Carter, 1982). The lower plate of the Vincent thrust consists of Pelona Schist--Mesozoic quartzofeldspathic sandstone and siltstone, limestone, quartzite, chert, and mafic volcanic rocks that have been metamorphosed to greenschist and lower amphibolite facies, presumably during late Mesozoic to early Tertiary emplacement of the upper plate (Ehlig, 1968b, 1981, 1982). From the Frazier Mountain region southeast to the Salton Trough, Pelona Schist occurs as windows and fault-bounded blocks (Ehlig, 1968b), including: (1) the Sierra Pelona window in the western San Gabriel Mountains; (2) the Lytle Creek window in the eastern San Gabriel Mountains; (3) the Blue Ridge slice between the Punchbowl and San Andreas faults; (4) a large window that mostly has been buried beneath sedimentary fill of the San Bernardino Valley; and (5) the Orocopia Mountains and Chocolate Mountains windows of Pelona-type schist that are referred to as Orocopia Schist and that are separated from rocks of San Gabriel Mountains-type by the Orocopia-Chocolate Mountain thrust. Both lower and upper plates are intruded by high-level Miocene granitoid plutons and dikes that were emplaced after initial juxtaposition of the two plates (Miller and Morton, 1977; Crowe and others, 1979).

Basement rocks of ***Peninsular Ranges-type*** (fig. 2B) consist of Jurassic and Cretaceous granitoid rocks (granodiorite, quartz diorite, tonalite, gabbro) that have intruded prebatholithic metasedimentary rocks (pelitic schist, metaquartzite, marble, quartzofeldspathic gneiss and schist). Along its north and northeast edge, the Peninsular Ranges block is bordered by a mylonitic belt of ductile deformation that separates lower plate plutonic and metasedimentary rocks of typical Peninsular Ranges type from broadly similar upper-plate rocks that appear to be parautochthonous equivalents of the more typical Peninsular Ranges suite; the autochthonous and parautochthonous suites have been telescoped along the mylonite zone (Sharp, 1979; Erskine, 1985). The ductile zone is referred to by different names locally, but Sharp (1979) recognized its regional significance and named it the Eastern Peninsular Ranges mylonite zone. The ductile zone probably continues westward into the southeastern San Gabriel Mountains, where mylonitic rocks have been mapped a few km north of the Mountain front (Alf, 1948; Hsu, 1955; Morton and Matti, 1987); if so, then the San Gabriel mylonitic belt may separate lower and upper plate rocks of Peninsular Ranges type--a speculative proposal we adopt here. Juxtaposition of Peninsular Ranges-type and San Gabriel Mountains-type rocks in the southeastern San Gabriel Mountains represents either (1) original intrusive relations between the two suites or (2) their tectonic juxtaposition by Neogene strike-slip displacements or (3) their tectonic juxtaposition by Paleogene or latest Cretaceous thrust faulting (May and Walker, 1989), or (4) a combination of some or all of these mechanisms.

Basement rocks of ***San Bernardino Mountains-type*** (fig. 2C) are similar to those in the Mojave Desert, and consist of Triassic through Cretaceous granitoid rocks of various compositions that have intruded prebatholithic orthogneiss (Proterozoic) and metasedimentary rocks (late Proterozoic and Paleozoic metaquartzite, marble, pelitic schist, and gneiss). The metasedimentary rocks are comparable with rocks of the Cordilleran miogeocline (Stewart and Poole, 1975). The Mesozoic plutonic rocks include both deformed and undeformed suites that extend southeastward into the Little San Bernardino Mountains, where they intrude rocks of San Gabriel Mountains-type. Strongly deformed Mesozoic granodiorite, tonalite, and quartz diorite form a discrete belt in the southeastern San Bernardino Mountains and along the western margin of the Little San Bernardino Mountains. Like rocks of San Gabriel Mountains-type, rocks of San Bernardino Mountains-type may be a layered terrane with batholithic and prebatholithic rocks in an upper plate separated from Pelona Schist in a lower plate by a low-angle fault comparable to the Vincent thrust.

RIGHT-LATERAL STRIKE-SLIP FAULTS

In the vicinity of the central Transverse Ranges, rocks of Peninsular Ranges type, San Gabriel Mountains type, and San Bernardino Mountains type are traversed by a series of northwest-trending strike-slip faults (fig. 1) that most workers assign to the San Andreas transform-fault system--a family of right-lateral faults that has evolved along the continental margin of western North America since middle Miocene time in response to interactions between the North American plate and various oceanic plates to the west (Atwater, 1970; Crowell, 1979; Dickinson and Snyder, 1979a,b). Youthful faults commonly viewed as modern components of the San Andreas system include the San Andreas fault proper; the San Jacinto, Whittier-Elsinore, and Newport-Inglewood faults; and various northwest-trending faults occurring in the offshore continental borderland (see Allen, 1957, p. 346; Crowell, 1975a, p. 10-11, 1981, p. 593). Older faults commonly viewed as abandoned components of the San Andreas system include the Punchbowl, San Gabriel, and Banning faults (Allen, 1957; Crowell, 1962, 1975a, 1981; Ehlig, 1976, 1981). Even older right-lateral faults that may belong to the San Andreas system include the San Juan-St. Francis and San Francisquito-Fenner-Clemens Well fault zones proposed in various forms by Smith (1977), Powell, (1981, 1986), and Joseph and others (1982b).

Right-lateral strike-slip faults in southern California are named and classified according to a hierarchical nomenclature that includes fault "strand", fault "zone", and fault "system" (Crowell, 1975a, p. 10-12): thus, the Mission Creek and Mill Creek strands (along with other fault strands) occur within the San Andreas fault zone that (along with other fault zones) occurs within the San Andreas fault system. Within this hierarchical classification, we adopt the fault nomenclature identified in Table 1 and map sheets 1 and 2.

SAN JACINTO FAULT ZONE

Within the Peninsular Ranges Province, the San Jacinto fault zone separates the San Jacinto Mountains and San Timoteo Badlands from the Perris block. In the San Jacinto Mountains the fault forms a series of en-echelen segments that locally are complicated by thrust faults (Sharp, 1967, 1972). A major right step in the fault zone occurs to the northwest in the San Jacinto Valley. There, the eastern right-stepping strand (Claremont fault) is located along the northeast side of the Valley and locally forms scarps in late Quaternary deposits; however, youngest Quaternary units are not broken and the fault largely must be inferred beneath sediment deposited by the San Jacinto River and by alluvial fans derived from the San Timoteo Badlands. To the west, a left-stepping strand of the San Jacinto zone (Casa Loma fault) is located along the southwest side of the San Jacinto Valley. The fault forms a scarp that Sharp (1972, map sheet 2) traced almost continuously from Hemet to north of the Lakeview Mountains. However, to the northwest the fault has no surface expression in youthful alluvium of the northern San Jacinto Valley, and slip must step right (east) onto the Claremont strand of the San Jacinto zone (J.C. Matti and D.M. Morton, in prep.). Within the Perris block, the San Jacinto fault has generated about 25 km of right-lateral displacement since early Pliocene time (Sharp, 1967; Matti and Morton, 1975).

Between the San Jacinto Valley and the San Gabriel Mountains the San Jacinto fault zone traverses Quaternary alluvial units and sedimentary rocks. In the Reche Canyon area the fault displaces strongly folded Quaternary deposits of the San Timoteo Badlands, and has a pronounced bow convex to the west that forms a restraining bend (Morton and Matti, in press); the main trace is flanked by subparallel faults (Morton, 1978a,b) that may be right-lateral in origin. Southeast of metropolitan San Bernardino the main trace displaces older and younger Quaternary units, but southeast and northwest of this break the youngest floodplain deposits of the Santa Ana River and Cajon and Lytle Creeks are not broken.

The distribution and geologic history of the San Jacinto fault in the southeastern San Gabriel Mountains are problematical. The name "San Jacinto" traditionally has been applied to a northwest-oriented fault zone developed in crystalline rocks east of the mouth of Lytle Creek canyon (fig. 3). There, the zone consists of two or more closely spaced fault strands that form impressive shear zones in crystalline bedrock but do not displace Quaternary alluvial deposits (Morton and Matti, 1987, plate 12.1). To the east, the Glen Helen fault forms scarps and sag ponds in alluvial deposits that probably are as young as Holocene (Sharp, 1972, map sheet 3; Morton and Matti, 1987, pl. 12.1), and to the west the Lytle Creek fault forms a scarp in alluvial materials that are latest Pleistocene in age (Morton and Matti, 1987, pl. 12.1). Mezger and Weldon (1983) documented a late Quaternary right-slip rate of about 2 mm/yr for the Lytle Creek fault. The Glen Helen fault probably is the active strand of the San Jacinto fault zone in the San Gabriel Mountain region, but it is unclear if this fault records the total history of the fault that developed southeast of the San Gabriel Mountains.

Models for the long-term history of the San Jacinto fault in the southeastern San Gabriel Mountains depend on how various bedrock faults that occur there are mapped and interpreted. Some workers indicate that the fault zone east of the mouth of Lytle Creek continues to the northwest and joins the San Andreas fault by way of the Punchbowl fault (Noble, 1954b; Ehlig, 1975, fig. 1, 1981, fig. 10-2). This interpretation leads to the idea that the San Jacinto fault feeds into the San Andreas, and that total slip on the San Andreas northwest of this junction includes displacements on the San Jacinto (Ehlig, 1982, p. 375; Weldon, 1984). However appealing, this model is questioned by other workers (Dibblee, 1968a, fig. 1, p. 266; 1975b, p. 156; Morton, 1975a, figs. 1, 2, p. 175) who conclude that the San Jacinto fault cannot be mapped into either the Punchbowl or San Andreas faults; instead, faults attributed to the San Jacinto zone appear to splay into several branches that curve west into the San Gabriel Mountains without joining the San Andreas fault at the surface (Morton, 1975a; Morton and others, 1983). This difference in structural interpretation has led to uncertainty about how the San Jacinto fault participates in the San Andreas fault system.

We propose that fault strands in the southeastern San Gabriel Mountains that originated by Quaternary right-slip on the San Jacinto fault can be understood only in the context of earlier Neogene faults that juxtaposed and rejuxtaposed rocks of Peninsular Ranges-type and San Gabriel Mountains-type. Figure 3 illustrates the pattern of Neogene faults in the southeastern San Gabriel Mountains and our interpretation of basement-rock provincial affinities (discussed below). In our discussion of the San Gabriel and Banning faults, we propose that the east- to northeast-oriented Evey Canyon, Icehouse Canyon, and Stoddard Canyon faults are segments of throughgoing structures that formerly were regionally extensive--namely, the middle Miocene left-lateral Malibu Coast-Raymond-Banning fault and the late Miocene San Gabriel-Banning fault. Moreover, we propose that these older faults separate rocks of San Gabriel Mountains-type on the west, north, and east from rocks of Peninsular Ranges-type on the south (fig. 3). In our model, these older structures trend essentially eastward until they enter the Lytle Creek drainage, where they converge and trend southeastward down Lytle Creek Canyon. There, they are represented by the fault zone that occurs east of the mouth of Lytle Creek Canyon. In our view, then, the name "San Jacinto fault" in Lytle Creek Canyon has been applied to an ancient fault zone that has witnessed multiple episodes of strike-slip faulting--only the latest of which can be attributed to the movement history of the fault called "San Jacinto" that traverses the Peninsular Ranges Province to the southeast. This composite movement history is consistent with the broad crush zone that marks the trace of the San Jacinto fault between the Icehouse Canyon fault and the mountain front, and accounts for the pronounced contrast in basement-rock types on either side of the crush zone (fig. 3; Morton and Matti, 1987, Plate 12.1).

Thus, earlier Neogene faulting in the southeastern San Gabriel Mountains established a structural template that has been modified by Quaternary right-slip within the San Jacinto zone. But where and how did Quaternary displacements occur in the mountains? To the southeast, within the Peninsular Ranges, 25 km of Quaternary right slip can be documented for the San Jacinto fault on the basis of displaced basement rocks (Sharp, 1967) and displaced Pliocene sedimentary rocks of the San Timoteo Badlands (Matti and Morton, 1975). The San Jacinto thus should be viewed as a strand of the San Andreas system, and an easy solution would have right-slip faults of the San Jacinto in the southeastern San Gabriel Mountains connect with the San Andreas northwest of Cajon Pass. However, we reiterate here that faults attributable to the San Jacinto cannot be mapped beyond the southeastern San Gabriel Mountains. Instead, right-lateral faults that might be attributable to the San Jacinto zone in Lytle Creek Canyon curve westward and southwestward into the San Gabriel Mountains and turn into east- to northeast-trending north-dipping faults that have reverse left-slip displacements (Morton, 1975a, figs. 1, 2). Morton (1975b) viewed the curving fault splays in the southeastern San Gabriel Mountains as a schuppen-like structure within which right slip on northwest-oriented strands of the San Jacinto is transformed into reverse left slip on east- and northeast-oriented faults that appear to be continuations of the San Jacinto zone.

We adopt Morton's (1975b) proposal here, but modify it to fit our notion that these curving faults were not pioneered by Quaternary slip but instead are older Neogene strands of the Malibu Coast-Banning and San Gabriel-Banning fault systems that have been reactivated and deformed during Quaternary time due in part to the 15° angular convergence between the San Jacinto and San Andreas faults (Morton and Matti, in press). We propose that one of these curving structures is the reactivated Stoddard Canyon segment of the San Gabriel fault that originally was a right-lateral structure but now has latest-movement indicators interpreted by Morton (1975a) as evidence for oblique left slip. A second oblique left-lateral fault (the San Antonio) trends down San Antonio Canyon and has displaced three fault segments of the old Malibu Coast-Banning system and the San Gabriel-Banning system (fig. 3): (1) the north branch of the San Gabriel fault about 3 km from the Icehouse Canyon fault, (2) the Evey Canyon fault about 3 km from the Icehouse Canyon fault, and (3) the south branch of the San Gabriel fault about 3 km from the Stoddard Canyon fault.

The oblique left-lateral faults all root eastward or northeastward into the northwest-oriented fault zones of Lytle Creek drainage that traditionally have been assigned to the San Jacinto fault. One of these strands apparently has generated at least 8 to 13 km of Quaternary right slip that has displaced plutonic contacts between Miocene granitoid rock and Pelona Schist (fig. 3; Morton, 1975a). However, even this displacement cannot be mapped northwestward out of the Lytle Creek drainage basin.

The structural complexity in the southeastern San Gabriel Mountains makes it unclear to us exactly how right slip on the San Jacinto has been transferred to the San Andreas. Two extreme interpretations apply: (1) right slip on the San Jacinto is transferred entirely to the San Andreas by way of a right-step that takes place between San Gorgonio Pass and the southeastern San Gabriel Mountains, or (2) right slip on the San Jacinto fault is transformed entirely into oblique left slip along faults within the southeastern San Gabriel Mountains, and thereby does not contribute at all to right slip on the Mojave Desert segment of the San Andreas. We suspect that kinematic interaction between the San Jacinto and San Andreas faults has involved both right-stepping slip transfer and left-stepping slip bypass, but until the relative scale of either process is documented, the amount of slip transfer from the San Jacinto to the Mojave Desert segment of the San Andreas can only be inferred. In the absence of actual data, we arbitrarily infer that 20 km of slip has been transferred between the two faults by way of the right step across the San Bernardino Valley; we infer that the remaining 5 km has been transformed into oblique left slip within the southeastern San Gabriel Mountains, where this transformation has led to convergence, uplift, block rotations, and severe shape changes of blocks bounded by brittle faults.

SAN ANDREAS FAULT ZONE

The main strand of the San Andreas fault in southern California consists of two segments (fig. 1): (1) the Mojave Desert segment that mainly separates rocks of San Gabriel Mountains-type from rocks of San Bernardino Mountains-type, and (2) the Coachella Valley segment that separates rocks of Peninsular Ranges-type from rocks of San Bernardino Mountains- and San Gabriel Mountains-type. In plan view the main strand has a left-stepping geometry: the Mojave Desert segment has been stepped left (west) about 15 km from the Coachella Valley segment, with the step occurring in the San Gorgonio Pass region of the southeastern San Bernardino Mountains (Matti and others, 1985). This left step forms a structural knot in the San Andreas that has influenced the evolution of the entire transform-fault system and has led to multiple fault strands that evolved sequentially. Multiple strands also have developed along the Mojave Desert segment of the San Andreas (Barrows and others, 1985, 1987). This strand complexity has made it difficult to identify the distribution and displacement history of faults in the San Andreas family, and has led to variable fault nomenclature and to conflicting fault-movement scenarios.

FAULT NOMENCLATURE

The complex pattern of late Cenozoic right-lateral faults in southern California has led to nomenclature for the San Andreas fault that is more complex than for central California. There, most if not all Miocene and younger displacement on the San Andreas has occurred within a narrow, singular (although complex) zone that extends the length of central California to Hill and Dibblee's (1953) "Big Bend" at the latitude of the Garlock fault. The name "San Andreas fault" has been used by most workers in central California (Hill, 1981), and little confusion has arisen with regard to which geologic structure bears the name "San Andreas fault" or whether multiple fault strands have generated sequential displacements. By contrast, the San Andreas fault in southern California consists of multiple strands, each representing some portion of the geologic history allocated to the more singular zone in central California (Noble, 1932; Dibblee, 1954, 1968a; Allen, 1957; Crowell, 1962; Woodburne, 1975; Matti and others, 1985). This structural complexity has presented two challenges: (1) to document the distribution of the various fault strands and to determine their sequencing and amount of right-lateral displacement, and (2) to establish nomenclature that provides a logical framework for understanding faulting history and for relating fault segments having similar and/or dissimilar movement histories.

A nomenclatural framework for the San Andreas fault in southern California has evolved through the efforts of many workers (see the historical review by Hill, 1981). Early workers recognized that the characteristic geomorphic and geologic features of the San Andreas rift zone in central California extend southeast beyond Hill and Dibblee's Big Bend region and intervene between the Mojave Desert and the massifs of Liebre Mountain and the San Gabriel Mountains. On this basis, the name "San Andreas fault" originally was extended into southern California. However, Noble (1926, 1932) was among the first to observe that the San Andreas in southern California splays into several major branches--some occurring close to each other within the narrow Mojave Desert zone, others forming discrete strands that follow independent traces many kilometers apart. As Allen (1957) pointed out, this strand complexity creates a dilemma: which strand should bear the name San Andreas fault and which strand generated the large displacements proposed by Hill and Dibblee (1953) for the fault in central California?

Whenever possible, we refer to the San Andreas fault proper in southern California by one of the specific strand names identified in Table 1. However, because each of these strands merged with or fed into the San Andreas fault in central California, each southern California strand during its lifetime represented the San Andreas before it was abandoned and succeeded by the next "San Andreas." This iterative pattern has culminated in the modern San Andreas fault in southern California--the genetically related set of strands that most workers believe originated onshore in reponse to Pliocene opening of the Gulf of California by sea-floor spreading and transform faulting (Atwater, 1970). The name San Andreas fault usually is applied to this modern strand. Within this complex geologic and nomenclatural framework, we use the term "San Andreas (*sensu lato*)" for all strands of the San Andreas in southern California that have fed into the central California segment of the fault and contributed to its total history; we use the term "San Andreas (*sensu stricto*)" for those strands in southern California that have contributed to displacements on the fault only in Pliocene and Quaternary time. Thus, we can refer to the San Andreas fault generically without reference to a particular strand, but at the same time distinquish between broader vs. narrower interpretations of the name.

MOJAVE DESERT SEGMENT

The Mojave Desert segment of the San Andreas fault extends from Tejon Pass to the San Bernardino valley, where it passes into the San Bernardino strand. The modern break forms a singular trace that runs the entire length of the segment (Ross, 1969) and describes a gently-curving arc having a regional strike of about N 60 W; in Tejon Pass the trace is deflected into the big bend of Hill and Dibblee (1953, p. 453). Ground rupture associated with the 1857 earthquake on the San Andreas fault occurred along the Mojave Desert segment from Tejon Pass to about Wrightwood (Sieh, 1978a), and the modern trace has been the site of recurring Holocene ground rupture (Sieh, 1978b, 1984; Weldon and Sieh, 1985).

The Mojave Desert segment has been described thoroughly by Barrows and others (1985, 1987) on the basis of detailed mapping by the California Division of Mines and Geology (Barrows, 1975; Kahle, 1975; Barrows, 1979, 1980; Barrows and others, 1976; Beeby, 1979; Kahle and others, 1975; Kahle, 1979; Kahle and Barrows, 1980). Their mapping shows that from Tejon Pass southeast to Elizabeth Lake the modern trace coincides with older traces to form a narrow fault zone having a relatively simple faulting history. By contrast, between Elizabeth Lake and Cajon Pass the modern trace is but one of several fault strands that form a zone several kilometers wide (see similar interpretations by Noble, 1926, 1933, 1954a,b; Wallace 1949; Dibblee, 1967a, 1968a, 1975b). Within this wide zone, fault strands like the Punchbowl, Nadeau, and Little Rock faults have evolved sequentially and been abandoned, culminating in the modern trace that apparently evolved no earlier than the Pleistocene (Barrows and others, 1985, p. 105-106).

Geologic setting in the San Gabriel Mountains

In the San Gabriel Mountains Barrows and others (1985, 1987; Barrows, 1987) recognize five discrete strands of the San Andreas fault including, from west to east, the Punchbowl, Nadeau south, Nadeau north, Mojave Desert, and Little Rock strands (we use the term "Mojave Desert strand" to designate the "main San Andreas trace" of Barrows and others, 1985, 1987). Careful mapping by Barrows and others (1985) shows that the Punchbowl, Nadeau (north and south branches), and Little Rock faults all are truncated on their northwest and southeast ends by the Mojave Desert strand of the San Andreas. Thus, they can be viewed as anastomosed and abandoned strands of the San Andreas that probably are related to strands of the fault farther to the southeast in the San Bernardino Mountains and (or) Salton Trough.

Regional correlation of the Punchbowl fault is of particular interest because the fault appears to be a significant strand of the San Andreas, and yet its isolated position outboard (west) of the main San Andreas trace makes its role in the overall history of the San Andreas difficult to evaluate. The fault extends for about 75 km along the northeast flank of the San Gabriel Mountains (fig. 1; Barrows and others, 1987). The strand is characterized by its locally sinuous trace and west-dipping reverse dips, a geometry attributed by Barrows and others (1987) to deformation following its right-slip history. The Punchbowl fault originally was identified by Noble (1953), who interpreted it as a reverse dip-slip fault and implied that it merged with the San Jacinto fault by way of the Glen Helen fault (Noble, 1954a,b). Subsequently, Dibblee (1967a, 1968a) showed that the Punchbowl fault is a right-lateral fault that he interpreted as an old strand of the San Andreas family. Because it is truncated on the southeast and northwest by younger strands of the San Andreas zone, the Punchbowl should be viewed like any other linear structure that has been displaced by a strike-slip fault: its northwest and southeast terminations have been displaced from cross-fault counterparts that should be identifiable after right slip is restored on younger strands of the San Andreas. This interpretation motivated us to search southeastward for a possible displaced counterpart for the Punchbowl fault on the opposite side of the main trace of the San Andreas.

Faulting chronology.--The multiple San Andreas strands in the San Gabriel Mountains evolved sequentially about 5 m.y. ago (Barrows and others, 1985, 1987). The Punchbowl fault appears to be the oldest strand, although Barrows and others (1987, p. 2, 84, 86) indicate that sequencing relations between the Punchbowl and Little Rock strands are not completely clear. According to Barrows (1987, p. 149-153, figs. 6-8), stratigraphic relations bertween the Punchbowl fault and sediments of the Juniper Hills Formation (of Barrows, 1987) indicate that the Punchbowl fault may have generated right slip continuously between early Blancan (5 Ma) and late Blancan time (2 Ma). However, the age of the Juniper Hills Formation is poorly constrained (Barrows, 1987, p. 129-130), and relevent beds in the unit cannot be confidently assigned to a particular part of the Blancan (A.G. Barrows, oral communication, 1990). The Nadeau faults appear to be Pliocene in age, while the Mojave Desert strand may have originated in middle Pleistocene time.

Displacement history.--Barrows and others (1985, Table 4, 1987 p. 86) were able to document no more than 102 km of right slip on all strands of the San Andreas fault in the eastern San Gabriel Mountains: 21 km on the main or Mojave Desert strand of the San Andreas; 16 km on the Nadeau fault (north and south branches); 21+ km on the Little Rock fault; and 44 km on the Punchbowl fault. Their estimates for the Punchbowl fault are comparable with those proposed by other workers. Dibblee (1967a, fig. 72; 1968a, p. 263-264, fig. 1) recognized between 32 and 48 km of displacement on the Punchbowl based on cross-fault correlations between the San Francisquito and Fenner faults, between marine rocks of the San Francisquito Formation, and between the Sierra Pelona and Blue Ridge windows of Pelona Schist. Farley and Ehlig (1977) and Ehlig (1981, fig. 10-4) proposed about 40 km of displacement based on their suggestion that the Punchbowl fault has displaced strata in Ridge Basin that contain polka-dot granite clasts from strata in the Punchbowl Formation that contain similar clasts. Barrows and others (1985, 1987) acknowledge that their total displacement for the San Andreas (102 km) is considerably less than the widely accepted displacement (240 km), and they point out that displacement on the Little Rock strand may be greater than the 21 km they were able to document. Their displacement estimate for the main San Andreas strand (21 km) also is considerably less than most workers would infer for the strand.

COACHELLA VALLEY SEGMENT

The Coachella Valley segment of the San Andreas fault is a relatively simple fault zone, although locally it is complicated by en-echelon strands and lateral splays (Clark, 1984). The segment is relatively straight and generally has a uniform regional strike of about N 45° W, although Bilham and Williams (1985) identified alternating segments 9 to 14 km long that have trends of N 40° W and N 48° W, repectively. Youthful tectonic landforms and faulted Holocene alluvial deposits indicate that the Coachella Valley segment is a modern neotectonic element (Keller and others, 1982), but the antiquity and tectonic significance of the segment cannot be judged because Quaternary and late Tertiary sediments of the Salton Trough conceal older rocks bearing evidence for its full history.

In the southern Indio Hills the Coachella Valley segment of the San Andreas fault is joined by another right-lateral fault (map sheet 1). Dibblee (1954, p. 26, pl. 2; 1968a; 1975a) referred to these two faults as north and south branches of the San Andreas fault, but Allen (1957, p. 336-339, p. 346) cited geologic relations that discouraged him from assigning the name San Andreas to any of the faults in this region. Accordingly, Allen (1957, fig. 1) applied the names Mission Creek fault and Banning fault, respectively, to Dibblee's north and south branches of the San Andreas.

We share Dibblee's view that the northern of his two branches is the main strand of the San Andreas fault in the Salton Trough, and that the name "San Andreas" can be properly applied to the strand. However, we are not certain that his south branch is a throughgoing strand of the San Andreas. Our nomenclature reflects these interpretations (map sheet 1). We refer to Dibblee's north branch as the Coachella Valley segment of the San Andreas fault, and we apply that nomenclature to the entire extent of the fault in the Salton Trough. Like Allen (1957), we refer to Dibblee's south branch as the Banning fault, and we believe that it is a reactivated segment of the ancestral late Miocene Banning fault (an idea proposed by Dibblee, 1975a, p. 134).

The southeast and northwest terminations of the Coachella Valley segment of the San Andreas involve complex interactions with other fault zones. To the southeast, surface expression of the segment terminates near the southeast margin of the Salton Sea, where it interacts with the Brawley seismic zone and the Imperial fault (Sharp, 1982; Johnson and Hill, 1982). Some workers view this segment of the San Andreas fault as the northwesternmost of a series of right-stepping transform faults that extend from the Gulf of California onshore into the Salton Trough (Moore and Buffington, 1968, fig. 4; Elders and others, 1972, fig. 1; Crowell and Ramirez, 1979; Lonsdale and Lawver, 1980, fig. 1; Crowell, 1981, fig. 18-4; Johnson and Hill, 1982, fig. 6; Curray and Moore, 1984, figs. 1, 9).

At its northwest end the regional strike of the Coachella Valley segment is deflected westward, and it splays into the Mission Creek and Mill Creek strands of the southeastern San Bernardino Mountains. We cannot prove that these multiple strands merge beneath the Coachella Valley because they are buried by unfaulted Quaternary alluvium where they exit the San Bernardino Mountains. However, their map pattern in the mountains strongly suggests that the strands coalesce southeastward, and by the simplest interpretation they ultimately form a single fault zone--the Coachella Valley segment of the San Andreas fault.

Northwest of Desert Hot Springs the Coachella Valley segment of the San Andreas fault loses its clear surface expression, and Holocene displacements have not been demonstrated for the segment. The fault forms conspicuous scarps in Quaternary alluvium southeast of Desert Hot Springs, and discontinuous scarps can be traced northwestward where they disrupt young (but not youngest) alluvium in the center of town (Clark, 1984). However, to the northwest, latest Quaternary alluvial fans that flank the Little San Bernardino Mountains are not disrupted by the fault. The late Quaternary history of the Coachella Valley segment has not been worked out in this region.

Displacement history.--Although small youthful displacements on the Coachella Valley segment of the San Andreas fault have been recognized on the basis of cross-fault correlations between Quaternary alluvial materials (e.g., Keller and others, 1982; Matti and others, 1985), large older displacements recognized on the basis of cross-fault correlation between Cenozoic and pre-Cenozoic units generally have not been recognized. In part this reflects the fact that older rocks of appropriate age containing evidence for large-scale displacements largely are buried by young Quaternary sediment that has filled the Salton Trough. In addition, the widely cited model for 240 km of Pliocene and Quaternary displacement on the San Andreas fault in effect has dampened the search for pre-Pliocene cross-fault counterparts in the Salton Trough because the 240-km model requires that pre-Pliocene rocks have been displaced completely out of the Salton Trough region.

A study by Dillon (1975) suggests that this may not be the case. In his study of the southern Chocolate Mountains, Dillon (1975, fig. 70, p. 334-365) proposed that rocks in the southeastern San Bernardino Mountains have been displaced from the southern Chocolate Mountains by 180 ± 20 km of right slip on the Coachella Valley strand of the San Andreas (Dillon's north branch of the San Andreas). Dillon's proposal is based on three cross-fault correlations: (1) crystalline rocks of San Gabriel Mountains-type northeast of San Gorgonio Pass correlated with similar rocks in the vicinity of Mammoth Wash in the Chocolate Mountains (Dillon, 1975, p. 59-60, 351-353); (2) the Miocene Coachella Fanglomerate in the Whitewater area correlated with the fanglomerate of Bear Canyon in the southern Chocolate Mountains (Dillon, 1975, p. 341-346); and (3) the inferred strandline position of the marine Imperial Formation in the Whitewater area correlated with the inferred strandline position for the marine Bouse Formation in the Chocolate Mountain region (Dillon, 1975, p. 347-350, fig. 69). Dillon's reconstruction contrasts with that of Peterson (1975), who restores the Coachella Fanglomerate farther south in the Salton Trough and calls for 215 km of displacement on the Coachella Valley strand of the San Andreas.

San Bernardino Mountains segment

The San Andreas fault within and adjacent to the San Bernardino Mountains consists of several strands that evolved sequentially and then were abandoned; to the northwest and southeast, these strands merge to form the Mojave Desert and Coachella Valley segments.

PREVIOUS INVESTIGATIONS

In his geologic reconnaissance of the eastern San Bernardino Mountains, Vaughan (1922) recognized that the region was traversed by two important faults--the San Andreas fault, which he projected through San Gorgonio Pass and eastward into the Coachella Valley, and a fault he named the Mission Creek fault, which he projected through the southeastern San Bernardino Mountains. Hill (1928) discussed the San Andreas fault and related faults in the vicinity of the San Bernardino Mountains and named the Pinto Mountain and Mill Creek faults.

Following the observation by Noble (1932) that the San Andreas fault zone southeast of Cajon Pass splits into several major branches, Allen (1957) and Dibblee (1968) addressed the distribution and nomenclature of faults in the vicinity of the San Bernardino Mountains. Allen (1957, fig. 1, p. 336-343) reviewed fault nomenclature used by earlier workers in the San Gorgonio Pass region and clarified the distribution of the Mill Creek fault (adopted from Hill, 1928), the Mission Creek fault (modified from Vaughan, 1922), the Banning fault (recognized originally by Vaughan, 1922, and defined and extended by Hill, 1928), and the modern San Andreas fault. Allen showed that the Mill Creek and Mission Creek faults are strands of the San Andreas fault zone, although he was unable to confirm or refute large right-lateral displacements on the strands. Between Cajon Pass and San Gorgonio Pass, Allen followed tradition by applying the name San Andreas fault to "the most aligned and obvious prolongation" of the San Andreas that extends southeast of Cajon Pass--that is, "the fault that lies at the foot of the San Bernardino Mountains and continues into San Gorgonio Pass. Within the Pass area, however, various structural complications make the continuity of the fault through this region doubtful" (Allen, 1957, p. 337). Allen's last sentence epitomizes the notion that San Gorgonio Pass is the site of a knot in the modern San Andreas fault system.

Dibblee modified the distribution and nomenclature of Allen's fault strands in the southeastern San Bernardino Mountains. In his geologic map of the San Gorgonio Mountain quadrangle, Dibblee (1964) equated his north branch of the San Andreas fault with Allen's Mill Creek fault, an interpretation he reiterated later (Dibblee, 1968a, p. 269). Dibblee apparently viewed Allen's Mission Creek fault as a splay of his north branch (Dibblee, 1968a, figs. 3, 4; 1975a, p. 127, figs. 1, 2) and it is not clear from these papers which structure has the greater displacement. Dibblee's recent work (Dibblee, 1982, p. 152, 161-165, figs 1, 4, and 8) clearly equates his north branch with Allen's Mill Creek fault and states that it generated large right-lateral displacements. Dibblee (1968a, p. 268) applied the term south branch of the San Andreas fault to the modern trace along the foot of the San Bernardino Mountains, and projected this trace southeastward through San Gorgonio Pass to join his south branch in the Coachella Valley (Dibblee, 1954). Dibblee's discussion of offsets on the south branch is confusing: he indicates minor displacements on the south branch between San Gorgonio River and San Gorgonio Pass but large displacements on the same strand along the base of the San Bernardino Mountains (Dibblee, 1968a, p. 268), without elaborating on this discrepancy.

Our concept of basement terranes and their bounding faults in the southeastern San Bernardino Mountains borrows some elements from both Allen and Dibblee, but departs from both in the details of fault distribution and movement history. Our view of fault relations is closer to Allen's scheme than to Dibblee's. Despite the unifying appeal of Dibblee's nomenclature, his concept of north and south branches of the San Andreas fault is too simplified and partly is in error as shown by later mapping (Ehlig, 1977; Farley, 1979; Matti and others, 1982a, 1983). Allen's (1957) interpretation of the Mill Creek and Mission Creek faults as independent strands that follow separate routes through the San Bernardino Mountains more accurately delineates the boundaries of crystalline terranes native and exotic to the southeastern San Bernardino Mountains, even though Allen was unable to use the significance of these terranes to reconstruct a comprehensive movement history for his fault strands. Although many workers have adopted Dibblee's nomenclature for the San Andreas fault in the south-central Transverse Ranges, we recommend that this nomenclature be abandoned because it does not accurately reflect the geologic relations.

GEOLOGIC SETTING

Wilson Creek and Mission Creek faults

The Wilson Creek and Mission Creek faults are major strands of the San Andreas fault in the south-central Transverse Ranges: both juxtapose exotic, far-travelled crystalline and sedimentary rocks against rocks native to the San Bernardino Mountains. Our recognition of two major fault strands in a region where only the Mission Creek fault has been mapped previously is based on relations in the Raywood Flat area of the southeastern San Bernardino Mountains (Matti and others (1983) and in the Mill Creek area (Matti and others, 1992).

Wilson Creek and Mission Creek faults in the southeastern San Bernardino Mountains

Within crystalline rocks of the southeastern San Bernardino Mountains, the Wilson Creek and Mission Creek faults are closely spaced and traverse the range along a gently bowed, east-trending arc. At the southwest end of this arc, the Wilson Creek and Mission Creek faults diverge and follow separate paths within and adjacent to the mountains. At the east end of this arc, the two faults apparently coalesce to form a single fault that continues southeastward beneath alluvium of the Coachella Valley (Matti and others, 1982a). There, the combined Wilson Creek-Mission Creek strands merge with the Mill Creek strand to form the Coachella Valley segment of the San Andreas fault.

Throughout the southeastern San Bernardino Mountains, the Mission Creek fault occurs outboard (south) of the Wilson Creek fault and bounds a distinctive terrane of crystalline rocks similar to those of the lower and upper plates of the Vincent thrust in the San Gabriel Mountains. These relations can be seen best in the headwaters of San Gorgonio River, where rocks outboard of the Mission Creek fault form two suites separated by a steeply dipping fault that probably originated as a low-angle segment of the region-wide Vincent-Orocopia-Chocolate Mountain thrust system. Lower-plate rocks are Pelona Schist that consist mainly of chlorite-albite-actinolite greenstone; upper-plate rocks are hornblende-bearing granitoid rocks and granitic gneiss that have strongly foliated and layered fabrics created by ductile and brittle-ductile deformation. Small bodies and lenses of the Triassic Lowe plutonic complex (of Joseph and others, 1982) occur locally in the upper-plate sequence (Farley, 1979). These lower- and upper-plate rocks are similar to those that occur in the same structural block in the nearby Crafton Hills, and both sequences in turn are similar to those in the eastern San Gabriel Mountains (Ehlig, 1968b, p. 301, fig. 1, locs. 6-8). These correlations form the basis for our interpreting rocks in the southeastern San Bernardino Mountains as San Gabriel Mountains-type.

Relations between the Mission Creek and Wilson Creek faults can be seen best in the vicinity of Raywood Flat north of San Gorgonio Pass, where the two faults parallel each other closely and separate three different assemblages of crystalline rock. The Wilson Creek fault separates granitoid and gneissic rocks native to the San Bernardino Mountains to the north from a slice of crystalline rocks of unproven provincial affinity to the south; we refer to this enigmatic slice as the Wilson Creek block. The Mission Creek fault bounds the Wilson Creek block on the south and separates it from rocks of San Gabriel Mountains type.

Our interpretations in the Raywood Flat area differ in detail from those of Ehlig (1977) and Farley (1979), who recognized that the Mission Creek fault zone is an important structural boundary but suggested a different interpretation for geologic features that we use to identify the Wilson Creek fault. Critical to any interpretation is the structural position of Pelona Schist and associated crystalline rocks that we believe are bounded by the Wilson Creek and Mission Creek faults.

Pelona Schist forms two bodies in the headwaters of San Gorgonio River (map sheet 2). We agree with Farley (1979), who includes the main Pelona Schist body with rocks of San Gabriel Mountains-type and separates this package from non-related rocks to the north by the Mission Creek fault (map sheet 2; Matti and others, 1983). A second slice of Pelona Schist and associated crystalline rocks just west of Raywood Flat is more problematical, and forms the basis for our recognition of the Wilson Creek fault as a structure distinct from the Mission Creek fault. Farley (1979) viewed the Raywood Flat Pelona Schist body as a fault-bounded slice caught up between two branches of his Mission Creek fault zone, and he concluded that this and the main Schist body belong together as one coherent terrane south of the main Mission Creek strand. In contrast, we believe that the two Pelona Schist bodies and associated crystalline rocks constitute two different assemblages bounded by two major strike-slip faults. The schist bodies differ in their pre-metamorphic stratigraphy, and crystalline rocks in fault contact with the Raywood Flat body are different from rocks of either San Gabriel Mountains-type or San Bernardino Mountains-type.

We use these differences to suggest that the Raywood Flat Pelona Schist body is not a slice caught up in a right-lateral fault zone (Farley, 1979) but instead is a window through crystalline rocks of the Wilson Creek block. By this interpretation, high-angle faults now bounding the window have reactivated and modified a thrust surface (the Vincent-Orocopia-Chocolate thrust) that formerly had a low-angle geometry. Upper-plate rocks of this window constitute rocks of the Wilson Creek block that appear to be unlike those native to the San Bernardino Mountains or those in the upper-plate of the Vincent-Orocopia thrust to the south. These observations lead to our conclusion that two exotic crystalline terranes separated by two major strands of the San Andreas fault occur in the southeastern San Bernardino Mountains: (1)

a terrane of San Gabriel Mountains-type rocks outboard (south) of the Mission Creek fault and (2) the Wilson Creek block between the Mission Creek and Wilson Creek faults.

At the west margin of the southeastern San Bernardino Mountains the Wilson Creek-Mission Creek couplet has been modified by low-angle faulting and cannot be recognized in its original configuration. In the headwater region of San Gorgonio River, crystalline rocks native to the San Bernardino Mountains have been thrust southeastward across the Wilson Creek-Mission Creek fault zone and across exotic crystalline rocks outboard of the zone (Farley, 1979; Matti and others, 1983). Low-angle faulting probably evolved as the Wilson Creek-Mission Creek fault couplet was rotated from its original northwest strike into the anomalous east to northeast strike it presently displays in this vicinity. Although the low-angle faults obscure the original course of the Wilson Creek and Mission Creek faults, our mapping and palinspastic reconstructions indicate that they originally continued through and beyond Banning Canyon.

Wilson Creek fault along the southwest margin of the San Bernardino Mountains

Faults we assign to the Wilson Creek strand of the San Andreas occur along the southwest base of the San Bernardino Mountains between Wilson Creek and Cook Creek (map sheets 1, 2). Along this reach, the strand forms a curving, locally sinuous trace sandwiched between the San Bernardino and Mill Creek strands of the San Andreas. Southeast of this reach, between Wilson Creek and Banning Canyon, the Wilson Creek fault either is concealed by Quaternary alluvium or is truncated and displaced by the younger Mission Creek or San Bernardino strands of the San Andreas fault. To the northwest, beyond Cook Creek, the Wilson Creek strand is truncated by the Mission Creek and San Bernardino strands.

Near Wilson Creek, its namesake, the fault enters the San Bernardino Mountains and traverses Yucaipa Ridge before descending into Mill Creek Canyon. To the west, the Wilson Creek fault adopts a more westerly trend and converges with the younger Mill Creek fault. The two faults parallel each other for a few miles before the Wilson Creek strand diverges in the Cook Creek drainage near San Bernardino and exits the San Bernardino Mountains. Along this segment the fault dips between 35° and 65° to the southwest. The 35° dip occurs near the Cook Creek drainage, where the Wilson Creek strand juxtaposes gneissic crystalline rocks against Tertiary sedimentary rocks. There, the low-angle movement zone has been interpreted as a landslide surface (Gary Rasmussen and Associates, unpublished geotechnical report on file with San Bernardino County; G. Rasmussen, oral commun., 1984); however, we interpret it as a segment of the Wilson Creek fault that has acquired a low-angle geometry. West of City Creek, isolated masses of gneissose rock mapped as landslide masses by Morton and Miller (1975, fig. 1c) may be klippe of Wilson Creek block emplaced along a south-dipping and locally north-dipping thrust segment of the Wilson Creek fault.

The distribution, movement sense, and signficance of the Wilson Creek fault are interpreted in different ways by different workers. In the vicinity of Yucaipa Ridge and Mill Creek Canyon, faults we assign to the Wilson Creek strand were mapped by Owens (1959), and by R.E. Smith (1959) who identified two fault segments (his South fault and Yucaipa Ridge fault) that he thought were unrelated. Matti and others (1985) combined Smith's South and Yucaipa Ridge faults into their throughgoing Wilson Creek fault. The distribution and displacement history of the fault were examined by Demirer (1986), by West (1987) who referred to the structure as the Yucaipa Ridge fault and restricted the name "Wilson Creek" to another fault zone in the Yucaipa Ridge area, and by Hillenbrand (1990) who mapped the Wilson Creek fault northwest to the Cook Creek area. All previous workers conclude that faults we assign to the Wilson Creek fault are minor structures having a dip-slip geometry.

Stratigraphic comparisons between Tertiary nonmarine sedimentary rocks traversed by the Wilson Creek fault have influenced investigators who view the fault as a minor structure. These rocks originally were grouped by Vaughan (1922) into his vaguely defined Potato Sandstone. In the Mill Creek area the rocks have been mapped and investigated by various graduate students (Smith, 1959; Owens, 1959; Gibson, 1964; Demirer, 1986; West, 1987; Hillenbrand, 1990). Recently, Matti and others (1992) proposed that Vaughan's Potato Sandstone can be separated into the Mill Creek Formation (modified from Gibson, 1964, 1971) and the Formation of Warm Springs Canyon, and they indicate that the two units are separated by the Wilson Creek fault (map sheet 2 of this report). Most workers (Dibblee, 1982; Demirer, 1986; Sadler and Demirer, 1986; West, 1987) recognize strong lithostratigraphic similarities between the units that we separate into two formations, and therefore see no need to juxtapose them along a fault having significant strike-slip movement. We believe that stratigraphic differences between the Mill Creek and Warm Springs Formations outweigh stratigraphic similarities between them (Matti and others, 1992). Moreover, basement rocks of the Wilson Creek block that underlie the Mill Creek Formation are dissimilar to those in the San Bernardino Mountains east of the Wilson Creek and Mill Creek faults, and if the Mill Creek fault is a relatively minor strand of the San Andreas (discussed below), then either the Wilson Creek fault or some other (unrecognized) fault is required to bring the Wilson Creek block into the region.

Mission Creek fault along the southwest margin of the San Bernardino Mountains

Matti and others (1985) inferred the existence of the Mission Creek fault along the southwestern base of the San Bernardino Mountains in order to explain the juxtaposition of San Gabriel Mountains-type basement rocks (upper- and lower-plate rocks of the Vincent thrust) against the Wilson Creek block and rocks of San Bernardino Mountains-type. Juxtaposition of these distinctive crystalline terranes can be documented in the southeastern San Bernardino Mountains where the Mission Creek fault separates rocks of San Gabriel Mountains-type from rocks native to the San Bernardino Mountains and from rocks of the Wilson Creek block (discussed above). Matti and others (1985) reasoned that the Mission Creek strand continues in the subsurface along the southwestern base of the San Bernardino Mountains, where the structure continues to separate outboard rocks of San Gabriel Mountains-type from rocks of the San Bernardino Mountains and the Wilson Creek block. Just as in the southeastern San Bernardino Mountains, where the Mission Creek fault is an older abandoned strand of the San Andreas (Matti and others, 1983, 1985), so too along the southwestern base of the San Bernardino Mountains the Mission Creek fault is an older fault either (1) buried under Quaternary surficial materials or (2) reactivated by the late Quaternary San Bernardino strand. In the latter case, the trace of the San Bernardino strand would mark the trace of the older Mission Creek strand.

Mill Creek strand

The Mill Creek fault was named by Hill (1928), but modern discussions of the fault date from Allen's (1957) clarification of its distribution and geologic setting; our mapping of the fault is similar to Allen's. Within the San Bernardino Mountains the Mill Creek fault occurs inboard (east) of the Wilson Creek and Mission Creek faults, and traverses the mountains along a relatively straight to slightly curving trace that has a regional strike of about N 70° W. The fault zone is relatively simple and narrow. Southeast of the San Bernardino Mountains the Mill Creek fault and the Wilson Creek and Mission Creek faults coalesce to form the Coachella Valley segment of the San Andreas fault. To the northwest the Mill Creek fault exits the mountains near San Bernardino and merges with the San Bernardino strand of the San Andreas fault.

At the southeast end of the San Bernardino Mountains, near the confluence of the North and South Forks of the Whitewater River, we map the Mill Creek fault differently than either Allen (1957) or Dibblee (1967b). Allen (1957, pl. 1) thought that the Mill Creek fault terminated in this vicinity after having traversed much of the San Bernardino Mountains to the west. Dibblee recognized that the fault (his north branch) must continue to the southeast; he (Dibblee, 1967b, 1975a) projected the Mill Creek fault eastward beneath alluvium of the Whitewater River and suggested that it truncates the Pinto Mountain fault. We map the Mill Creek fault differently, and propose that it is deflected by the Pinto Mountain fault (Matti and others, 1982a, 1983). Where it obliquely exits the San Bernardino Mountains southeast of the Whitewater River, the Mill Creek fault flanks the mountain front and is located close to but north of the combined traces of the Mission Creek and Wilson Creek faults (Matti and others, 1982a, 1983).

San Bernardino strand

As defined by Matti and others (1985), the San Bernardino strand denotes the modern trace of the San Andreas fault in the vicinity of the San Bernardino Mountains. The fault extends for 60 km along the base of the Mountains from Cajon Pass southeast to the vicinity of Banning Canyon, and describes a gently curving arc that is convex to the south. To the northwest the San Bernardino strand is continuous with the modern trace of the Mojave Desert segment of the San Andreas; to the southeast the strand appears to terminate within the San Gorgonio Pass fault zone.

The San Bernardino strand coincides spatially with the projected trace of the Mission Creek fault, and probably evolved by reactivation of that older strand. By this interpretation, the Mission Creek fault is responsible for juxtaposing exotic far-travelled Pelona Schist bedrock of the San Bernardino valley against the Wilson Creek block to the north, and the San Bernardino strand is only a relatively recent break that developed within or close to the older fault.

We recognize three segments of the San Bernardino strand: a segment extending from Cajon Pass to the vicinity of Mill Creek, a segment extending from Mill Creek to the vicinity of Banning Canyon, and a segment extending from Banning Canyon to the Burro Flats area north of San Gorgonio Pass. Distinction between these three segments is based on contrasts in geologic structure and tectonic geomorphology.

Cajon Pass-Mill Creek segment.--The San Bernardino strand between Cajon Pass and Mill Creek is characterized by its conspicuous geologic and geomorphic expression, by its overall simplicity, and by abundant evidence for youthful activity: (1) The segment is relatively continuous and only slightly curved, and is not sinuous. It does not have significant left or right steps along its trace, although minor steps between overlapping fault segments occur locally. (2) Youthful activity along the segment is indicated by well developed primary fault features (scarps, sag ponds, pressure and shutter ridges) and by youthful geologic and physiographic features (alluvial fans, landslides, drainage lines) that have been offset by the fault throughout Holocene time. The fault cuts and forms scarps in all Holocene alluvial units, except for the youngest active stream alluvium. In the active sediments, shallow ground water is backed up behind the fault and its trace is marked by linear vegetation lines. (3) The San Bernardino Mountain front along the segment generally has low topographic relief, particularly to the northeast (Weldon and Meisling, 1982; Weldon, 1983), although relief gradually increases southeastward toward Mill Creek. These relations indicate that this segment of the San Bernardino strand has not generated significant amounts of vertical displacement (Weldon, 1985b). (4) In Cajon Pass the segment has a well documented Holocene slip rate of about 25 mm/year (Weldon and Sieh, 1985). Rasmussen (1982) indicates a similar rate of Holocene slip near San Bernardino.

Mill Creek-Banning Canyon segment.--Between Mill Creek and Banning Canyon the San Bernardino strand is characterized by its lack of clear continuous geomorphic expression and by its structural complexity locally.

Between Santa Ana River and the canyon mouth of Mill Creek, the San Bernardino strand maintains its regional strike of about N 70° W but becomes increasingly complex. Directly west of Mill Creek, bedrock and surficial units are traversed by several parallel fault strands, some of which are part of the San Andreas zone; locally, these strands have north-facing scarps (Matti and others, 1992). None of these faults breaks youngest deposits of Mill Creek wash, but on the east side of the wash vintage aerial photographs reveal a scarp that disrupts surficial deposits that have attributes of soil-stage S6 or S7 of McFadden (1982), and the unit probably is middle to late Holocene in age.

Southeast of Mill Creek the San Bernardino strand adopts a regional trend of about N 55° W, is complex structurally, and is complicated by landslide masses that have been shed from the Mill Creek Formation on Yucaipa Ridge (map sheet 2; Matti and others, 1992). These landslides have numerous crown scarps that resemble scarps created by faults, and it is difficult to associate any of these geomorphic features with the San Bernardino strand. The antiquity of the landslide masses is unknown. Whatever their age, right-slip on the San Bernardino strand has not displaced them laterally to any measurable degree. This reflects either (1) the youthfulness of the landslides or (2) the fact that the San Bernardino strand may step left around and beneath the landslide masses (Matti and others, 1992), in the process leaving most of them effectively attached to the Yucaipa Ridge block. We favor the latter hypothesis.

The left-stepping geometry is more conspicuous to the southeast toward Wilson Creek (Harden and Matti, fig. 2). In plan view, the fault pattern here consists of short northwest-trending fault segments that pass into northeast-trending fault-like scarps. The latter probably are north-dipping reverse faults, but we have not confirmed this speculation; in other fault systems, reverse dip-slip fault segments are common within left-stepping right-lateral strike-slip fault zones, and their occurrence in this vicinity would be compatible with the apparent left-stepping geometry of the San Bernardino strand along this reach. Locally, stream gullies and other geomorphic features have been displaced right-laterally by the northwest-trending fault segments. This evidence for youthful right-slip on the San Bernardino strand southeast of Mill Creek Canyon is complemented by convincing evidence for longer term right-slip throughout the latest Pleistocene and Holocene (Harden and Matti, 1989).

Between Wilson Creek and Banning Canyon the trace of the San Bernardino strand is not well defined, and it may have local left steps. Primary fault features generally are not common between Wilson Creek and Banning Canyon, and geologic and geomorphic evidence for youthful right-lateral activity is not obvious. The segment does not appear to cut or form scarps in youngest Holocene alluvial units, and the fault trace locally is overlapped by unfaulted landslide deposits. The San Bernardino Mountain front along the segment has considerable topographic relief, culminating in a 5,000-foot escarpment near Banning Canyon. This suggests that significant vertical movements have occurred along the segment.

Banning Canyon-Burro Flats segment.--Along the Banning Canyon-Burro Flats segment the regional strike of the San Bernardino strand turns abruptly southeastward toward San Gorgonio Pass. Southeast of Banning Canyon the fault zone is marked by springs, bedrock scarps, and lineaments, and Allen (1957), Dibblee (1975a, 1982), and Farley (1979) report that the fault forms a gouge zone in the crystalline rocks. Farther southeast, in an alluviated intermontane area known as Burro Flats, youthful-appearing northwest-trending en-echelon scarps that disrupt Holocene alluvial deposits and Pleistocene landslide debris may have been formed by the modern San Andreas fault. However, the origin of these scarps is questionable: they face northeast and have trends that are similar to other northeast-facing scarps in the region that are not part of the San Andreas fault zone (for example, the family of northeast-facing scarps on the Beaumont Plain), and it is possible that they formed within an extensional strain field rather than by right-slip along the trace of the modern San Andreas fault. If so, then there may be no evidence for recent activity on the San Bernardino strand (modern San Andreas) southeast of Banning Canyon. If they were formed by the San Andreas, these scarps are the southeasternmost evidence for a surface trace of the San Bernardino strand: between Burro Flats and the Banning fault, alluvial deposits are not cut by faults attributable to the San Andreas, and bedrock exposures are not traversed by major fault zones.

Lack of fault features led Allen (1957) to conclude that the modern San Andreas fault (our San Bernardino strand) dies out before reaching San Gorgonio Pass, although Dibblee (1968a, 1975a, 1982) concluded that the fault (his south branch) continues through San Gorgonio Pass and into the Coachella Valley. We do not know if the San Bernardino strand is continuous between Banning Canyon and San Gorgonio Pass or if it has generated the full right-lateral displacement (3 km) that we recognize in the vicinity of Mill Creek (discussed below). The total displacement gradually may fall off between Mill Creek and Burro Flats, so that the fault in the vicinity of San Gorgonio Pass has considerably less displacement and may not have been active recently. We tentatively agree with Allen's conclusion that the modern San Andreas fault dies out southeastward before it reaches San Gorgonio Pass.

GEOLOGIC HISTORY, SAN BERNARDINO MOUNTAINS SEGMENT, SAN ANDREAS FAULT

The San Bernardino Mountains segment of the San Andreas fault consists of four separate fault strands that evolved sequentially; each strand generated right-lateral displacements during a specific period and then was abandoned and succeeded by a younger strand. We have determined the sequence in which the four strands evolved, but we have not confirmed the timing and amount of displacement for all of them. Even though some elements of their movement history are ambiguous, however, one fact seems clear: together, the four strands record the total history of the San Andreas fault (*sensu stricto*) since its inception 4 or 5 m.y. ago.

Sequencing relations

The relative sequence in which the four strands evolved can be determined from structural relations between them and by the alluvial units that overlap the strands or are broken by them. The Wilson Creek fault is the oldest strand, followed sequentially by the Mission Creek, Mill Creek, and San Bernardino strands.

The Wilson Creek fault is demonstrably older than the Mission Creek fault because the Mission Creek truncates faults we interpret as part of the Wilson Creek strand and because the trace of the Wilson Creek everywhere is more curving and discontinuous than that of the Mission Creek. These relations suggest that the Wilson Creek fault is an older strand that was deformed and then succeeded by the less sinuous Mission Creek fault. The Mill Creek fault is younger than either the Wilson Creek or Mission Creek faults because it displaces late Quaternary gravel units that are not broken by either of the older faults (discussed below). The San Bernardino strand is the youngest of the four strands, and forms the modern trace of the San Andreas fault in the San Bernardino Mountains segment.

Faulting chronology

Wilson Creek and Mission Creek faults.--Our conclusion that the four strands of the San Bernardino Mountians segment record the full history of the San Andreas fault (*sensu stricto*) requires that the oldest strand--the Wilson Creek fault--developed when the San Andreas first evolved. The timing of initial movements on the Wilson Creek fault cannot be determined directly from relations in the San Bernardino Mountains but can be inferred from relations elsewhere in the region.

In the Whitewater area, south of all strands of the San Andreas fault but north of the Banning fault, Miocene and Pliocene sedimentary units all record about the same amount of right-lateral displacement from their probable depositional positions. Relevant units include the Coachella Fanglomerate, which is about 10 m.y. old (Peterson, 1975), and unconformably overlying beds of the Painted Hill and Imperial Formations, older parts of which are 6 m.y. old and older (Table 2). Dillon (1975, p. 334-365, fig. 70) proposed that the San Andreas fault has displaced the Coachella Fanglomerate and Imperial Formation from cross-fault counterparts in the southern Chocolate Mountains, a proposal we accept here. Moreover, conglomeratic beds of the Painted Hill Formation contain clasts that indicate source areas east of the southern Salton Trough. The fact that the Miocene Coachella Fanglomerate and unconformably overlying late Miocene and Pliocene units all record the same displacement requires that the San Andreas fault displaced them together during an episode of right-lateral faulting that commenced after 6 Ma. This timing is compatible with the proposed inception of the San Andreas fault (*sensu stricto*) in southern California, which most workers link with the onset of seafloor spreading in the Gulf of California and northwestward propagation of the East Pacific Rise (Moore and Buffington, 1968; Larson and others, 1968; Atwater, 1970; Elders and others, 1972; Moore, 1973; Crowell, 1979, 1981). The precise timing of this event is disputed, but about 4 or 5 Ma is a widely cited figure. Thus, initial movements on the Wilson Creek strand of the San Andreas fault occurred after 6 Ma and probably during the earliest Pliocene, 4 or 5 m.y. ago.

Initiation of the San Andreas fault (*sensu stricto*) also has been linked with termination of movement on the San Gabriel fault. According to Crowell (1982, p. 35, fig. 12), major right-lateral activity on the San Gabriel fault ceased about 5 m.y. ago when the Pliocene Hungry Valley Formation began to accumulate in Ridge Basin. Crowell suggests that right-slip was initiated on the San Andreas at or slightly before that time, although sequencing relations between deposition of the Hungry Valley Formation and initial movements on the San Andreas fault have not been documented.

Eclipse of the San Gabriel fault by the San Andreas fault about 5 m.y. ago corresponds nicely with the maximum age suggested for opening of the Gulf of California (4.9 m.y. ago according to Curray and Moore, 1982). Curray and Moore (1984) proposed a two-phase model for the geologic history of the Gulf: an early phase of diffuse extension, crustal attenuation, and rifting that may have been accompanied by formation of oceanic crust without lineated magnetic anomalies, followed time-transgressively by a later phase of opening accompanied by formation of lineated magnetic anomalies. The early extensional phase commenced 5.5 m.y. ago, but the actual opening phase commenced at about 4.9 Ma and culminated at about 3.2 Ma. Thus, the San Gabriel fault waned, the San Andreas fault (*sensu stricto*) evolved, and the Gulf of California opened--all about 4.9 m.y. ago. Linkage between these events needs to be documented, however, and this scenario has problems. For example, Curray and Moore (1984, p. 29) conclude that 300 km of right-slip on the combined San Andreas and San Gabriel faults correponds with the 300-km separation of Baja California from mainland Mexico, and that right-slip along the onshore faults commenced 5.5 m.y.B.P. This interpretation is in conflict with the onshore evidence (Crowell, 1981, 1982; Ehlig, 1981; Matti and others, 1986; Matti and Morton, 1992), and illustrates the lack of congruence between onshore and offshore histories.

We have not documented the timing of critical events like the duration of right-slip activity on the Wilson Creek and Mission Creek faults or when the Wilson Creek fault was eclipsed by the Mission Creek fault. These elements of faulting history require information about total displacement, rate of slip, and (or) the age of sedimentary units that date the critical events--questions that presently are unanswered by our studies.

The timing of latest strike-slip displacements on the Wilson Creek and Mission Creek faults is clearer than the timing of their early activity. In the vicinity of Whitewater River and Mission Creek, both faults are buried by Pleistocene gravel deposits (Matti and others, 1982a) that bear stage-S2 soils of McFadden (1982) and thus are at least 0.5 m.y. old (McFadden, 1982, p. 55-64, 344-349, 352-354, fig. 16). Farther west, in the Raywood Flat area, the two faults are buried by Pleistocene gravels that appear to correlate with those in the Whitewater-Mission Creek region. Farther northwest, between Banning Canyon and the Cajon Pass region, the Wilson Creek and Mission Creek faults are buried wherever they are associated with Quaternary alluvium.

The absence of primary fault features provides additional evidence for inactivity on the Wilson Creek and Mission Creek faults during late Quaternary time: neither fault displays scarps, sag ponds, shutter or pressure ridges, or right-laterally offset drainage lines. A degraded north-facing scarp that traverses Pleistocene gravels in the Raywood Flat area (Matti and others, 1983) is a possible exception. The scarp is associated with a north-dipping fault noted by Ehlig (1977) and mapped by Farley (1979); the fault breaks the Raywood Flat gravels at their east margin and drops them down to the north. Both Ehlig (1977) and Farley (1979) cite this fault as evidence for youthful right-lateral activity within the Mission Creek-Wilson Creek fault zone. However, we interpret it as a normal dip-slip fault that is part of a family of late Quaternary dip-slip faults in the region that have northeast- or north-facing scarps. The fault coincides with, and has reactivated, the Wilson Creek-Mission Creek fault zone in the vicinity of Raywood Flat, but diverges from it farther west (Matti and others, 1983). Thus, we conclude that the Wilson Creek and Mission Creek strands are abandoned right-lateral faults that have been bypassed by the San Andreas system.

Mill Creek fault.--The Mill Creek fault is a late Quaternary strand that is younger than the Wilson Creek and Mission Creek strands but older than the San Bernardino strand. The fault probably has not been a throughgoing right-lateral strand of the San Andreas during Holocene and latest Pleistocene time, and we propose that it has been abandoned and bypassed by the San Andreas system. Locally, the strand has been reactivated by dip-slip movements that have formed north-facing scarps in alluvium and in bedrock.

If our observation is correct that it has displaced Pleistocene gravel deposits and pre-Pleistocene crystalline rocks by about the same amount (discussed below), then the Mill Creek fault generated all of its right-slip displacement during late Pleistocene time. Faulting occurred more recently than about 0.5 Ma, the minimum age for Pleistocene gravel deposits displaced the full amount by the fault: (1) Gravels in the vicinity of Mission Creek and Whitewater River that are displaced 8 to 10 km from possible cross-fault counterparts north of Desert Hot Springs bear stage-S2 soils (McFadden, 1982, p. 55-64) and are at least 0.5 m.y. old; (2) gravels in the vicinity of Raywood Flat that have been displaced about 8 km from Hell For Sure Canyon and the North Fork of the Whitewater River are late Pleistocene, and probably are the same age as those in the vicinity of Mission Creek.

The Mill Creek fault is not a modern neotectonic strand of the San Andreas fault. For most of its extent, the fault is buried by Holocene and latest Pleistocene alluvial deposits. This relation can be observed at several localities between Waterman Canyon and the head of Mill Creek Canyon. Moreover, the strand does not form primary fault features such as sag ponds, shutter and pressure ridges, and right-laterally offset drainage lines. Scarps occur along some segments of the fault: for example, in the Harrison Mountain and San Bernardino North 7.5' quadrangles (Morton and Miller, 1975; Miller, 1979), north- and northeast-facing scarps disrupt bedrock and older Pleistocene alluvial deposits (Allen, 1957, p. 343); the sense of displacement indicated by scarps and faulted contacts is down on the north. Latest displacements on the Mill Creek fault in this vicinity probably represent dip-slip reactivation of the strand, and the north-side-down movements may be related to partial subsidence of the San Bernardino Mountains following their uplift during the Pleistocene (Weldon and Meisling, 1982; Meisling, 1984; Weldon, 1983, 1985b).

North of Raywood Flat the Mill Creek fault zone may have been the site of modern movements, but we have not determined their recency or sense of displacement. At the head of the Middle Fork of Whitewater River (the Middle Fork Jumpoff), alluvial units overlying the crush zone of the Mill Creek fault are broken by a conspicuous fault plane that dips steeply to the north and drops alluvial deposits to the north against crystalline rocks to the south (Allen, 1957, pl. 1; Farley, 1979, p. 86-88, fig. 9). This fault appears to form a degraded north-facing scarp that can be traced a short distance west from the Middle Fork Jumpoff (J.C. Matti and J.W. Harden, unpubl. data). The faulted alluvial deposits are a north- and south-thinning wedge of colluvial sand and gravel derived from highlands to the north and south. Uppermost layers of the north-thinning wedge are youthful and have only incipient soil-profile development. It is not clear if these youngest deposits are faulted, or if they buttress depositionally against the degraded fault scarp.

Several problems plague this locality: (1) The age of the faulted alluvial deposits has not been determined, nor have their stratigraphic and paleogeographic relations to Pleistocene fluvial gravels of the nearby Raywood Flat area that have been displaced 8 km by the Mill Creek fault. (2) It is not clear that the obvious fault plane represents strike-slip movements on the Mill Creek fault--most of whose crush zone is buried by the alluvial deposits--or activity on one of the other numerous faults that traverse the Raywood Flat region. It is possible that the fault plane, with its north-facing scarp and down-on-the-north separation, represents dip-slip displacements like those that have occurred on the Mill Creek fault farther to the west. Available data do not confirm or refute Holocene right-slip displacements on the Mill Creek fault here or to the east. Farley (1979) explored the possibility that youthful displacements have occurred on the fault east of the Middle Fork Jumpoff, but have died out to the west. Our data cannot rule out this proposal. However, because of the absence of primary fault features throughout most of the alluvial cover here, we suspect that the fault in this region has not generated throughgoing right-lateral displacements since latest Pleistocene time.

San Bernardino strand.--The San Bernardino strand is the modern neotectonic component of the San Andreas fault in the vicinity of the south-central Transverse Ranges, and has generated right-lateral displacements throughout Holocene and latest Pleistocene time. If the strand has maintained the 25 mm/year Holocene slip rate determined for the fault in Cajon Pass (Weldon and Sieh, 1985), and if it has generated no more than about 3 km of displacement, then right-slip on the modern neotectonic trace of the San Andreas fault in the Transverse Ranges segment commenced about 120,000 yr. ago.

Although the San Bernardino strand apparently did not generate ground ruptures during the 1857 earthquake (Sieh, 1978a,b), it should be viewed as a fault capable of generating large or even great earthquakes (Allen, 1968, 1981; Sieh, 1981; Rasmussen, 1981; Raleigh and others, 1982; Lindh, 1983; Nishenko and Sykes, 1983; Sykes and Seeber, 1982; Sykes and Nishenko, 1984; Ziony and Yerkes, 1985; Wesson and Wallace, 1985; National Earthquake Prediction Evaluation Council, 1988). Most earthquake scenarios for this part of southern California incorporate ground-rupture lengths of several hundred kilometers and moment magnitude of 8 or greater (Raleigh and others, 1982; Sykes and Nishenko, 1984; Lindh, 1983). Some workers suggest that an earthquake comparable to the 1857 event might lead to ground rupture on the San Bernardino strand northwest through Cajon Pass and onto the Mojave Desert segment, and possibly southeast through San Gorgonio Pass and into the Coachella Valley region where other neotectonic components of the San Andreas fault would be activated. Such scenarios need to be tested in a rigorous way, however, and other scenarios may be possible (Rasmussen, 1981; Weldon and Sieh, 1985, p. 811-812). Ground-rupture patterns within the San Andreas fault zone will become more predictable only when we understand the overall fabric of a region where the San Andreas fault is only one of several neotectonic elements.

Amount of displacement: previous interpretations

Following Crowell's (1962) proposal that the San Andreas fault in southern California has 210 km of right-lateral displacement, many workers have attempted to apportion this displacement among various San Andreas strands in the southeastern San Bernardino Mountains. Gibson (1964, 1971) inferred on the basis of paleocurrent and clast-provenance studies that the Mill Creek fault has displaced the Miocene Mill Creek Formation (of Gibson, 1971) about 120 km from its original position adjacent to the Orocopia Mountains. Dibblee (1968a, p. 269) concluded that, if Crowell's 210 km of right slip has occurred along strands of the San Andreas in the San Bernardino Mountains, then the largest movement probably occurred along his north branch (Mill Creek fault). Later, Dibblee (1975a, p. 134) proposed that the north branch generated about 96 km of right slip and displaced crystalline rocks in the southeastern San Bernardino Mountains from presumed cross-fault counterparts in the Orocopia Mountains. Dibblee (1982b, p. 164) subsequently increased this value to 120 km--a displacement identical to Gibson's (1964, 1971) and presumably based on Gibson's palinspastic restoration of the Mill Creek strata to the Orocopia Mountains region.

Neither Gibson (1964, 1971) nor Dibblee (1968a, 1975a) accounted for the large difference between their proposed displacements on the Mill Creek fault (96 to 120 km) and Crowell's (1962) proposal for total displacement on the San Andreas (210 km). This difference presumably was made up by other faults in the region. However, Dibblee (1968a, p. 168) had ruled out his south branch of the San Andreas because the fault has only a few km of right slip in the San Gorgonio Pass area, leaving only the Banning and San Jacinto faults to take up the missing 90 km. However, neither of these faults qualifies for the following reasons: (1) the Banning did not generate right-lateral displacements at the same time as the San Andreas (*sensu stricto*) and therefore does not figure into the 210-km reconstruction proposed by Crowell (1962); (2) the San Jacinto has no more than 25 or 30 km of displacement (Sharp, 1967); and (3) neither fault figures into palinspastic reconstruction of rocks in the southeastern San Bernardino Mountains because both faults pass outboard of that region.

Dillon's (1975) proposal that the north branch of the San Andreas has displaced rocks in the southeastern San Bernardino Mountains from counterparts in the southern Chocolate Mountains (discussed above) provided a major alternative to the proposals by Gibson and Dibblee. Dillon's displacement on Dibblee's north branch (180±20 km) is considerably greater than the displacements proposed by Gibson and Dibblee (96 to 120 km), but both estimates seemed equally attractive based on the merits of their underlying cross-fault correlations.

This conflict was resolved by later studies in the San Bernardino Mountains that reinterpreted the bounding faults between distinctive basement terranes. Ehlig (1977), Farley (1979), and Matti and others (1983a, 1985) showed that the Mill Creek fault (Dibblee's north branch) does not form a major break between crystalline rocks as Gibson (1971) and Dibblee (1968a, 1975a, 1982a) believed. Instead, lithologic similarities between crystalline rocks on either side of the fault preclude large right-lateral displacements on this strand of the San Andreas (Matti and others, 1985, p. 9). Thus, the Mill Creek fault could not have displaced Gibson's Mill Creek strata by more than a few kilometers from their depositional position. Building on Ehlig's (1977) earlier work, Farley (1979) demonstrated that the major lithologic break between crystalline rocks is formed by the Mission Creek fault of Allen (1957)--an interpretation refined by Matti and others (1983a, 1985). This fault--not the Mill Creek strand (Dibblee's north branch)--was shown to be the San Andreas strand that juxtaposed rocks of San Gabriel Mountains-type against rocks of San Bernardino Mountains-type as proposed by Dillon (1975; see Farley, 1979, p. 120-129; Matti and others, 1985, p. 9-10). This clarified the distribution of major basement terranes and their bounding faults and set limits on displacements for individual strands, but left two factors still unresolved: (1) the palinspastic position of the Mill Creek Formation alleged to have originated near the Orocopia Mountains and (2) the 40-km to 80-km discrepancy between Dillon's estimate of 180±20 km of displacement on the San Andreas and the widely cited estimate of 240 km (upgraded by Crowell, 1975a, 1981, and Ehlig, 1981, from Crowell's original estimate of 210 km).

The slip discrepancy was reemphasized when Matti and others (1985, 1986) proposed that total right slip on the San Andreas fault in the vicinity of the San Bernardino Mountains may be no more than 160±10 km. This estimate corresponds nicely with the lower limit of Dillon's estimate of 180±20 km, and both proposals indicate that estimates of 210 to 240 km for total right slip on the San Andreas fault (*sensu stricto*) in southern California may be too large. We adopt this position, and use the 160-km displacement together with estimates for displacement on other strands of the San Andreas zone to reconstruct fault-movement histories for individual strands of the San Andreas in the vicinity of the San Bernardino Mountains.

Amount of displacement: new possibilities

Our conclusion that the Wilson Creek, Mission Creek, Mill Creek, and San Bernardino strands record the full history of the San Andreas fault (*sensu stricto*) requires that their individual displacements sum to the total displacement on the fault in southern California. Estimates for this total range from less than 100 km to 270 km, but the most widely cited studies have focused on a range of 210 km (Crowell, 1962) to 240 km (Crowell, 1975a; Ehlig and others, 1975; Ehlig, 1981, 1982). By contrast, Matti and others (1985, 1986; Frizzell and others, 1986) concluded that the San Andreas fault in southern California probably has no more than 160±10 km of total displacement. This smaller displacement is based on the proposal that distinctive bodies of Triassic megaporphyritic monzogranite that occur in the Mill Creek region of the San Bernardino Mountains (Monzodiorite of Manzanita Springs of Morton and others, 1980; unit Trm of Matti and others, 1992) and in the Liebre Mountain area on the opposite side of all strands of the San Andreas fault represent segments of a formerly continuous pluton that was severed and displaced by the fault. We adopt the 160-km displacement, and apportion it between the four strands of the San Bernardino Mountains segment of the San Andreas fault.

San Bernardino strand.--We propose that the San Bernardino strand has no more than 3 km of displacement. This hypothesis is based on evidence from Pleistocene alluvial deposits and crystalline bedrock that occur south of the fault between Mill Creek and the Santa Ana River. The gravels were deposited by ancestral streamflows of Mill Creek, and contain several distinctive clast types traceable to bedrock sources drained by the modern stream Since their deposition, the gravels have been displaced no more than 3 km by the San Bernardino strand (Matti and others, 1992). The gravel deposits are capped by soil profiles that have thick, well developed, red argillic horizons comparable to those in old Pleistocene soils (stage S2 soils of McFadden, 1982). The bedrock is a slice of crystalline rock from the Wilson Creek block; although we cannot identify an exact cross-fault counterpart for this slice, it constrains right-lateral displacements on the San Bernardino strand to no more than 3 km.

Mill Creek strand.--Available evidence suggests that the Mill Creek fault has no more than 8 to 10 km of right-lateral displacement. This conclusion is based on four separate geologic relations:

(1) In the vicinity of Raywood Flat, thick deposits of Quaternary gravel appear to have been displaced about 8 km by the Mill Creek fault (Sheet 2, A-A', B-B'). The gravel was derived primarily from crystalline-rock sources north of the fault and was deposited in an intermontane-valley setting. The bilobate shape of the gravel body suggests that the alluvial fill was derived from two large converging drainages lying to the north of the Mill Creek fault. Such drainages do

not exist north of the present position of the Raywood Flat area, but two drainages with the appropriate size, orientation, and spacing do exist east of this area and north of the Mill Creek fault--the North Fork of the Whitewater River and Hell For Sure Canyon. These two large drainages most likely were the source for the Quaternary fill in the Raywood Flat area--a paleogeographic reconstruction requiring about 8 km of right-slip on the Mill Creek fault since deposition of the Raywood Flat gravels.

(2) Bodies of metaquartzite, marble, and minor schist that occur on both sides of the fault on the north and south flanks of Mill Creek Canyon appear to be parts of a single metasedimentary sequence that has been severed by the fault and displaced no more than 10 km (Sheet 2, C-C'). The metasedimentary bodies, first mapped by Dibblee (1964), occur in Mill Creek Canyon on the north side of the Mill Creek fault and on Yucaipa Ridge on the south side of the fault. Farley (1979, p. 107, fig. 13) reasoned that the two metasedimentary bodies could be displaced counterparts, but he discounted their exact cross-fault correlation because of differences in lithologic detail; instead, he cited them as evidence for the overall lithologic similarity of rocks on either side of the Mill Creek fault. Detailed differences in lithology and stratigraphic sequence exist between the two bodies, but we attribute these to metamorphic modification that occurs along strike in both areas and we interpret the two bodies as displaced counterparts.

(3) Bodies of distinctive granodioritic orthogneiss (orthogneiss of Alger Creek of Matti and others, 1992) that occur on both sides of the fault in Mill Creek Canyon appear to be severed parts of a single pluton that have been displaced no more than about 10 km (Sheet 2, D-D').

(4) Pleistocene gravel deposits overlying the Coachella Fanglomerate in the vicinity of the Whitewater River and Mission Creek drainages (Matti and others, 1982a) are similar to, and have some clast types in common with, gravel deposits north of the Coachella Valley segment of the San Andreas fault near Desert Hot Springs (Sheet 2, E-E'). Dibblee (1967b) originally assigned the Desert Hot Springs gravels questionably to the Miocene Coachella Fanglomerate, but they probably are Quaternary (Proctor, 1968). Restoration of about 8 to 10 km on the Mill Creek fault and the Coachella Valley segment of the San Andreas aligns the gravels north of Desert Hot Springs with those in the vicinity of Mission Creek and Whitewater River, which suggests that the two deposits may be parts of a coalescing alluvial-fan complex that since has been displaced by the Mill Creek strand.

Thus, available evidence from both crystalline rocks and Quaternary alluvial deposits indicates that the Mill Creek strand of the San Andreas fault has no more than 8 to 10 km of right-lateral displacement, and is not a major strand of the San Andreas fault.

Mission Creek and Wilson Creek strands.- Displacements on the Mission Creek and Wilson Creek faults presently cannot be determined directly on the basis of specific cross-fault correlations. Originally, we proposed that the two faults are major strands of the San Andreas that in combination have brought exotic rocks against the San Bernardino Mountains from original positions as much as 150 km farther southeast in the Coachella Valley region (Matti and others, 1985, p. 9-10). We proposed that the Wilson Creek strand had considerably more displacement than the Mission Creek strand, but we acknowledged the uncertainties in this model and pointed out that an equally likely reconstruction of displaced crustal blocks could be achieved if the Mission Creek fault, rather than the Wilson Creek fault, had the larger displacement. We now favor this role reversal between the two fault strands.

We assign right-slip estimates to the Mission Creek and Wilson Creek faults based on three arguments: (1) the hypothesis that these two faults, along with other strands of the San Andreas system, have displaced the Mill Creek and Liebre Mountain Triassic megaporphyry bodies by no more than 160 km; (2) cross-fault correlation between rocks of San Gabriel Mountains-type in the southeastern San Bernardino Mountains and similar rocks in the Chocolate Mountains (Dillon, 1975); and (3) correlation of fault segments in the San Bernardino Mountains with other fault strands of the San Andreas zone in the San Gabriel Mountains.

As discussed by Matti and Morton (in press), total displacement on the San Andreas fault (*sensu stricto*) in the vicinity of the San Bernardino Mountains is the sum of displacements on individual faults that jointly have displaced the Liebre Mountain megaporphyry body away from its cross-fault counterpart in the Mill Creek region:

$$A + B + C + D + E = 160 \text{ km},$$

where A = San Bernardino strand, B = Mill Creek strand, C = San Jacinto fault, D = Mission Creek strand, and E = Wilson Creek strand.

The slip equation can be partly solved using the following values:

A = about 3 km of right slip on the San Bernardino strand. This displacement has fed into the Mojave Desert segment of the San Andreas.

B = about 8 km of right slip on the Mill Creek strand. This displacement fed into the Mojave Desert segment of the San Andreas.

C <25 km of right slip on the San Jacinto fault. Our original estimate for strand displacements in the San Bernardino Mountains (Matti and others, 1985) did not incorporate the notion that slip on the San Jacinto fault has contributed to northwestward displacement of the Liebre Mountain megaporphyry body away from the San Bernardino Mountains. Our current interpretation is that most of the 25 km of right-slip proposed by Sharp (1967) for the San Jacinto fault in the Peninsular Ranges steps right from the San Jacinto fault to the San Andreas fault between San Gorgonio Pass and Cajon Pass, and thereby contributes to total slip on the Mojave Desert segment of the San Andreas (Matti and others, 1985; Morton and Matti, in press). The full 25 km may not have been transferred, however, because an unknown percentage of slip on the San Jacinto has been dissipated by extension within the right-stepping region of the San Bernardino Valley and absorbed by convergence within the Cucamonga fault zone and uplift of the southeastern San Gabriel Mountains (Matti and others, 1982b, 1985; Morton and Matti, 1987; Morton and Matti, in press). In this report we arbitrarily apportion 20 km of right slip on the San Jacinto fault to the San Andreas and 5 km to contractional and extensional deformation related to strain transfer between the San Jacinto and San Andreas faults.

Using slip data for A, B and C, the displacement equation is complete except for D and E, displacements on the Mission Creek and Wilson Creek faults:

$$3 \text{ km} + 8 \text{ km} + 20 \text{ km} + D + E = 160 \text{ km}.$$

Assuming values A, B, and C are correct and sum to 31 km, then values D and E (the combined displacements on the Mission Creek and Wilson Creek faults) sum to 129 km. Compare this value with the 150-km displacement we originally proposed for combined slip on the Mission Creek and Wilson Creek faults when we did not take into account slip contributed by the San Jacinto fault.

To arrive at values for D and E in the displacement equation, we turn to strike-slip faults in the San Gabriel Mountains that might be counterparts of either the Mission Creek fault or the Wilson Creek fault. Given our conclusion that the Mission Creek strand is middle Pliocene and younger in age and is a major fault that juxtaposed rocks of San Gabriel Mountains-type and San Bernardino Mountains-type, its counterpart in the San Gabriel Mountains should include faults of the same age that also juxtapose the two crystalline suites. By these criteria the Mission Creek strand is correlative with the Mojave Desert strand, which must be viewed as a major strand of the San Andreas that has a right-slip history extending from the present back to at least middle Pleistocene (Barrows and others, 1985, 1987). Although Barrows and others (1987, p. 2, 83, 85) indicated that the Mojave Desert strand (their "main trace") may be no older than 1 to 1.4 Ma, they (1987, p. 82) also pointed out that ". . . all rock units older than late Pleistocene that are juxtaposed along the main trace are dissimilar. . . ." We take this to mean that the Mojave Desert strand is the major trace of the San Andreas in the vicinity of the San Gabriel Mountains, and is responsible for juxtaposing rocks of San Gabriel Mountains-type against rocks of San Bernardino Mountains-type. Like other workers, we suspect that the Mojave Desert strand has a longer-lived history than proposed by Barrows and others (1985, 1987). Thus, we correlate the Mission Creek strand (and the younger Mill Creek and San Bernardino strands) with the Mojave Desert strand (and potentially with the Pliocene Nadeau faults).

If the Mission Creek and Mojave Desert strands are the major throughgoing traces of the San Andreas, then restoration of significant slip on that strand together with restored slip on the Mill Creek and San Bernardino strands would bring the northwest termination of the Punchbowl fault near Palmdale (fig. 1) closer to the southeast termination of the Wilson Creek fault in the southeastern San Bernardino Mountains. We propose that the Wilson Creek and Punchbowl faults originally formed a single throughgoing structure that was severed by younger strands of the San Andreas fault; the displaced segments of the once-continuous structure now are situated in the San Bernardino and San Gabriel Mountains. Comparison of the Wilson Creek and Punchbowl faults is supported by three lines of evidence: (1) they generated right-lateral displacements during the same time period (5 or 6 Ma to about 3.5 Ma, although Barrows, 1987, would have activity on the Punchbowl fault be as young as 2 Ma); (2) they both have sinuous traces and west-dipping reverse dips; and (3) they both bound crystalline-rock slices (the Wilson Creek block and crystalline rocks of Pinyon Ridge in the San Gabriel Mountains) that have no documented affinity with particular crystalline terranes in southern California but are broadly similar to each other. We propose that the Punchbowl and Wilson Creek strands of the San Andreas once formed a continuous throughgoing right-lateral fault that had about 40 to 45 km of displacement based on estimates for the Punchbowl fault in the San Gabriel Mountains. In this report, we use the 40-km figure and insert this value for E in the displacement equation.

Using slip data for A, B, C, and E, the displacement equation

$$3 \text{ km} + 8 \text{ km} + 20 \text{ km} + D + 40 \text{ km} = 160 \text{ km}$$

can be solved for D, yielding a displacement of 89 km for the Mission Creek strand of the San Andreas fault.

SYNTHESIS

Available data lead to a preliminary history of the San Andreas fault in the vicinity of the Transverse Ranges (fig. 4):

(1) Following inception of the San Andreas fault 4 or 5 m.y. ago, about 40 km of right-slip on the throughgoing Wilson Creek-Punchbowl fault juxtaposed exotic crystalline and sedimentary rocks of the Wilson Creek block against the San Bernardino Mountains (fig. 4A). Rocks native to the San Bernardino Mountains, including Triassic megaporphyritic monzogranite discussed by Matti and others (1986; Frizzell and others, 1986), were displaced to the northwest by these offsets, and the Wilson Creek block and Mill Creek Formation were juxtaposed against rocks native to the San Bernardino Mountains. During this period, the Wilson Creek-Punchbowl fault probably was a straight throughgoing strand that was continuous to the northwest and the southeast with the Mojave Desert and Coachella Valley segments of the San Andreas fault.

(2) Right-slip on the Wilson Creek-Punchbowl fault terminated when it was deformed into a sinuous trace and was bypassed by the Mission Creek fault (fig. 4B). This event occurred adjacent to the left-lateral Pinto Mountain fault, and left the Wilson Creek block stranded against the San Bernardino Mountains block. Thereafter, the San Bernardino and Wilson Creek blocks functioned as a single structural unit, with the Wilson Creek block behaving as though it was native to the region.

(3) The Mission Creek fault juxtaposed Pelona Schist and associated upper-plate rocks like those in the eastern San Gabriel Mountains against the Wilson Creek block (fig. 4C). The throughgoing Mission Creek fault was continuous to the northwest and southeast with the Mojave Desert and Coachella Valley segments of the San Andreas. Ultimately, the Mission Creek fault and adjacent rocks were deflected to the west and southwest as a left step developed in the San Andreas fault (fig. 4D), and the strand was abandoned and bypassed by the San Andreas transform system.

(4) The Mill Creek fault evolved inboard of the locked up Mission Creek fault (fig. 4E), and generated about 8 km of right-lateral displacement during the late Pleistocene (after about 0.5 Ma). Subsequently, the Mill Creek fault was deformed and apparently abandoned as a throughgoing right-lateral fault.

(5) The San Bernardino strand marks the trace of the modern neotectonic strand of the San Andreas fault within the Transverse Ranges segment (fig. 4F). This strand probably has reactivated the older Mission Creek strand in the vicinity of the San Bernardino valley.

Discussion

Several questions can be asked about the history of the San Andreas fault in the vicinity of the south-central Transverse Ranges. Why did several strands evolve? By what mechanism was each strand deformed and succeeded by a younger strand, and how much time did such a transition involve? Were there gaps in right-slip activity on the San Andreas fault during these periods? If so, did right-slip transfer from the San Andreas to some other fault in the San Andreas transform system? What impact did deformation of the Wilson Creek and Mission Creek faults have on the region? Or alternatively, were these two faults deformed in passive response to other events in the region? Does the Pliocene and early Pleistocene history of the San Andreas fault provide a precedent for the modern neotectonic framework? Some of these questions can be addressed on the basis of existing data.

Several unique Pliocene-Pleistocene structural and physiographic elements coincide in the vicinity of the south-central Transverse Ranges--a juxtaposition that implies a cause-and-effect relation. The most important elements are (1) the multiple deformed strands of the San Andreas fault; (2) the Pinto Mountain fault, a major left-lateral structure that generated about 16 km of displacement (Dibblee, 1968b); and (3) the San Bernardino Mountains, a major physiographic element created by Pleistocene orogenesis (Meisling, 1984; Meisling and Weldon, 1989). Various authors have discussed the history of the San Andreas fault in the context of these unique structural and physiographic elements.

Allen (1957) contributed many original concepts, including (1) the idea that the present surface geometry of faults in the San Gorgonio Pass region differs from their original orientation parallel to the northwest regional strike of the San Andreas fault, and (2) the idea that faults of the San Andreas system are vying with east-oriented faults of the Transverse Ranges for structural control of the region. Allen (1957, p. 344-346, fig. 3) evaluated the structural setting of the San Gorgonio Pass region from the viewpoint of a regional triaxial strain field incorporating a principal stress direction oriented N-S and an intermediate stress direction that alternates between the E-W and vertical axes. Allen proposed that right-slip on San Andreas-type faults predominated when the intermediate stress was oriented vertically, but thrust faulting (and presumably left-slip on structures like the Pinto Mountain fault) predominated when the intermediate stress was oriented E-W. Allen's analysis applied mainly to Quaternary thrust faulting in San Gorgonio Pass, but by implication extends to the paleotectonic history of the Banning and San Andreas faults. The triaxial-strain concept was embellished by Farley (1979, p. 115-120) and by Crowell and Ramirez (1979, p. 31-32, 39), who evaluated relations between the San Andreas fault and the Pinto Mountain fault from the viewpoint of conjugate shear within a region undergoing simple shear.

Dibblee (1975a) evaluated the history of the south-central Transverse Ranges by relating deformation of the San Andreas fault to left-lateral displacements on the Pinto Mountain fault, and by relating these events in turn to uplift of the San Bernardino Mountains. In his analysis, left-lateral displacements on the Pinto Mountain fault impinged on the San Andreas and created a bottleneck that impeded throughgoing right slip; as a consequence, the Banning fault and segments of his north and south branches in the San Gorgonio Pass region were bent into east-west orientations, and the San Bernardino Mountains evolved through compressional uplift (Dibblee, 1975a, p. 134-135; 1982b). He suggested that these events occurred in late Quaternary time. Farley (1979, p. 115-129) envisioned a similar scenario, although he interpreted strands of the San Andreas fault differently than Dibblee and suggested that deformation of the San Andreas and Banning faults by left-slip on the Pinto Mountain fault occurred during late Pliocene time.

We agree that structural and physiographic elements in the south-central Transverse Ranges are linked in their evolution, but we differ from earlier workers in our view of how the various elements interacted with each other. For example, Dibblee (1975a, p. 134-135) and Farley (1979, p. 115-129) both suggest that left-slip on the Pinto Mountain fault deflected the Banning fault and all strands of the San Andreas fault during a single period of deformation. By contrast, we believe that the Banning fault acquired its east-trending orientation prior to inception of the San Andreas fault 5 m.y. ago, and that the Wilson Creek, Mission Creek, and Mill Creek faults each were deformed separately during compressional episodes that were followed by right-slip on the succeeding strand.

It seems certain that deformation of the San Andreas fault in the south-central Transverse Ranges is linked with orogenic uplift of the San Bernardino Mountains, but linkage between the two events cannot be documented in detail because their timing is known only in a general way. Recent studies suggest that uplift of the mountains commenced less than about 2.6 m.y. ago (Sadler, 1982a,b; May and Repenning, 1982; Weldon and Meisling, 1982; Meisling and Weldon, 1982, 1989; Sadler and Reeder, 1983; Meisling, 1984). We can demonstrate that the Mission Creek fault was being deformed during the Pleistocene and was abandoned before 0.5 m.y. ago, thus linking uplift and strand deformation during later parts of the Quaternary.

The Pinto Mountain fault probably played a role in the interaction between the San Andreas fault and the San Bernardino Mountains--although more likely as an effect than as a cause. The history of the Mission Creek fault may have bearing on the history of the Pinto Mountain fault. In the southeastern San Bernardino Mountains, the Mission Creek fault has a concave-south trace that occurs outboard of crystalline rocks native to the region. This curving geometry apparently was achieved as a bulge of San Bernardino Mountains basement was projected west and southwest across the path of the fault during the late stages of its activity--an event that accompanied deformation of the strand into its curving trace (fig. 4B,C, fig. 5). Left-slip on the Pinto Mountain fault could have achieved this effect by displacing the southeastern corner of the San Bernardino Mountains west and southwest relative to the little San Bernardino Mountains. The Pinto Mountain fault need not have truncated and offset the Mission Creek fault by this process: instead, gradual projection of the San Bernardino Mountains across the path of the San Andreas merely could have deflected or bowed the Mission Creek strand into a curved trace (fig. 5). When the curvature became too great to sustain right-slip, the Mission Creek was succeeded by other faults in the San Andreas family, including the San Jacinto fault zone and the Mill Creek strand (fig. 4C).

It is unclear whether left-slip on the Pinto Mountain fault continued throughout the history of the Mission Creek fault, thereby causing slow progressive deformation of the strand, or whether the Mission Creek fault enjoyed an early history of right-slip unimpeded by regional compression. Ultimately, however, continued left-slip on the Pinto Mountain fault projected the San Bernardino Mountains farther across the path of the San Andreas fault, and the Mission Creek strand was abandoned and bypassed by the San Andreas transform system before 0.5 Ma (fig. 4D). The evolving intersection between the Mission Creek and Pinto Mountain faults probably resembled the curving intersection between the modern San Andreas fault and the Garlock fault in the Big Bend of the Tejon Pass region. Westward projection of the San Bernardino block created a significant geometric effect (fig. 5): the Mojave Desert and Coachella Valley segments of the San Andreas fault have been stepped left from each other by about 15 km, which is about the amount of left-lateral displacement on the Pinto Mountain fault (Dibblee, 1968b).

The Mill Creek fault did not exist when the Mission Creek fault was deformed, but subsequently broke in behind the barrier imposed by the bent and locked-up Mission Creek strand. This event occurred after about 0.5 Ma. Subsequent displacements on the Mill Creek fault sliced off the westward projection of the San Bernardino Mountains block created by left-lateral displacements on the Pinto Mountain fault. Ultimately, renewed left-slip on the Pinto Mountain fault kinked the Mill Creek fault in the vicinity of the Whitewater River Forks, and the Mill Creek fault, too, has been abandoned by the San Andreas system.

The history of the San Bernardino Mountains segment of the San Andreas fault may have included one or more slip gaps filled by other faults in southern California. For example, some authors have suggested that the San Jacinto fault evolved when right-slip on the San Andreas was impeded in the vicinity of the southeastern San Bernardino Mountains (for example, Crowell, 1981, p. 597), and that accelerated or deccelerated slip on these two faults may have alternated through time (Sharp, 1981, p. 1761). The long-term slip rate for the San Bernardino Mountains segment of the San Andreas fault may well have varied through time, but such a scenario can be documented only when the timing and amount of right-lateral displacements on the Mission Creek and Mill Creek strands of the segment are better understood.

SAN GABRIEL FAULT

Geologic setting

The San Gabriel fault extends southeastward from Ridge Basin to the western San Gabriel Mountains, where most workers recognize north and south branches (fig. 1). The north branch curves eastward through the San Gabriel Mountains to the southeastern part of the range, where its eastward continuation is obscured by a complex network of faults (Morton, 1975a). The south branch traverses the south flank of the San Gabriel Mountains, where the fault is obscured by the Quaternary frontal-fault zone that bounds the south margin of the mountains. Most workers suggest that the south and north branches rejoin in the vicinity of the eastern San Gabriel Mountains, but this structural reunion has not been documented and each worker has suggested a different arrangement of linking faults (contrast the views of Dibblee, 1968a, fig. 1, 1982a, fig. 1; Ehlig, 1973, fig. 1 and 1981, fig. 10-2; Crowell, 1975a, fig. 1; 1975c, p. 208-209; 1982a, fig. 1). According to the generally accepted view, the combined south and north branches of the San Gabriel fault must work their way through the structural complexity of the eastern San Gabriel Mountains and continue eastward.

Continuity of the San Gabriel fault southeast and northwest of its mapped distribution is problematical. Matti and others (1985) proposed that the Banning fault forms the southeastward continuation of the San Gabriel fault. We elaborate this proposal below. Northwestward continuation of the San Gabriel fault beyond Ridge Basin is obscured by Quaternary thrust faults that carry crystalline rocks of the Frazier Mountain region southward over the San Gabriel fault and associated sedimentary rocks of Ridge Basin. There, most workers follow Crowell (1950, 1975a, 1982a, figs. 3, 4) who proposed that the San Gabriel fault at depth continues northwestward beneath the thrust sheets to join the San Andreas fault (Crowell, 1982a, p. 29). We interpret this junction as a meeting point where an older fault (the San Gabriel) intersects a younger fault (the San Andreas, *sensu stricto*), and we view the northwest end of the San Gabriel fault as a piercing point whose palinspastic position should be identifiable after right-slip is restored on the San Andreas (*sensu stricto*). When we restore 160 km of right slip on the Mojave Desert segment of the San Andreas, the northwest end of the San Gabriel fault restores to the Cajon Pass region where the Cajon Valley fault (fig. 1) may represent a former continuation of the San Gabriel fault (Matti and Morton, 1992).

Displacement history

Estimates for right slip on the San Gabriel fault range from 0 to 70 km. Crowell (1952) first proposed large lateral displacements based on his recognition that distinctive Precambrian basement clasts in the upper Miocene Violin Breccia of Crowell (1954a) in Ridge Basin and in upper Miocene marine beds of the Modelo Formation have been displaced 30 to 35 km from likely cross-fault sources in the Frazier Mountain region and western San Gabriel Mountains, respectively. However, Paschall and Off (1961) discounted the role of right slip on the San Gabriel fault and instead accounted for the distribution of basement clasts in the sedimentary units purely on the basis of vertical dip-slip movements. Crowell (1962, p. 39-40) reiterated his proposal that clasts in sedimentary rocks require about 32 km of displacement on the San Gabriel fault, and also suggested that basement rocks in the Frazier Mountain region may have been displaced by as much as 48 km from cross-fault counterparts in the western San Gabriel Mountains (Crowell, 1962, p. 41). Carman (1964) called for about 32 km of right slip on the fault based on his proposal that upper Miocene nonmarine deposits of the Caliente Formation in the Lockwood Valley area were part of the same fluvial drainage that deposited the Mint Canyon Formation in Soledad basin; the two parts of the fluvial system since have been displaced by the San Gabriel fault. This proposal was expanded and refined by Ehlig and others (1975), who used stratigraphic patterns of distinctive volcanic clasts and basement-rock clasts to propose that the Caliente-Mint Canyon drainage was disrupted by as much as 56 to 65 km of right slip on the San Gabriel fault. Ehlert (1982b) subsequently increased this estimate to 70 km. Ehlig and Crowell (1982) subsequently refined the basement-rock correlations originally cited by Crowell (1962), and concluded that the San Gabriel fault has displaced these rocks by about 60 km. This figure has become widely accepted as the total displacement on the San Gabriel fault. In the San Gabriel Mountains, the 60-km displacement presumably is split between the north and south branches of the fault: about 22 km on the north branch, as shown by displaced crystalline rock units (Ehlig, 1968a), and the remaining 38 km presumably on the south branch, although this displacement has not been proven by cross-fault correlations. We propose that the San Gabriel fault has no more than about 44 km of displacement: 22 km on the north branch (Ehlig, 1973), and 22 km on the south branch based on our proposal that the fault has displaced the left-lateral Malibu Coast-Santa Monica-Raymond fault from the Evey Canyon-Icehouse Canyon fault in the southeastern San Gabriel Mountains (discussed below).

Crowell (1982a, fig. 12) proposed that right slip on the San Gabriel fault was initiated in the late Miocene (about 10 m.y. ago) and largely was completed by the end of the Miocene (about 5 Ma). Late Miocene onset of faulting is interpreted from interfingering stratigraphic relations between the syntectonic Violin Breccia and marine sediments of late Miocene age. Termination of strike-slip displacements on the San Gabriel fault by earliest Pliocene time is interpreted from relations in Ridge Basin, where the Pliocene Hungry Valley Formation of Crowell (1950) has been mapped as a depositional cap that seals the main displacement history of the San Gabriel fault (Crowell, 1982c). The basal part of the Hungry Valley Formation is about 5 m.y. old, and Crowell (1982a,b) concluded that right slip within the San Andreas transform system switched from the San Gabriel fault to the San Andreas fault at about this time. However, this conclusion has been questioned by some workers, most notably Weber (1982) who indicates that the Hungry Valley sequence is disrupted by the San Gabriel fault and that a few km of right slip on the San Gabriel occurred after the Hungry Valley was deposited.

BANNING FAULT

Previous investigations

Vaughan (1922) first mapped faults later referred to the Banning fault; his map shows these as unnamed faults that extend west from their juncture with the San Andreas fault in the east part of San Gorgonio Pass. It is clear from Vaughan's text (1922, p. 399-401) that he viewed the San Andreas fault as the dominant structure in San Gorgonio Pass; he attached no particular significance to the unnamed faults that he recognized to the west. Hill (1928) reinterpreted fault relations in San Gorgonio Pass and introduced the name "Banning fault" for the fault segments that Vaughan (1922) first identified. Although Hill (1928, plate II) did not specifically designate the Banning fault on his map, he evidently applied the name to a fault he showed extending from the east part of San Gorgonio Pass west to the San Jacinto fault and beyond; he did not indicate an identifiable extension of the Banning fault eastward into the Coachella Valley. Hill (1928, p. 142) indicated that the fault Vaughan had called the San Andreas in the east part of San Gorgonio Pass did not extend to the northwest as Vaughan believed, but instead continued west to the fault segment that Vaughan had not named or evaluated.

Allen (1957) clarified many of the geologic and nomenclatural problems associated with the Banning fault zone, and his report has formed the basis for all later discussions of the zone. Allen recognized that the Banning fault not only is an important zone of crustal convergence, as indicated by the zone of thrust and reverse faults associated with the fault in San Gorgonio Pass, but also is an important strike-slip fault with as much as 11 to 19 km of right-lateral offset. Reexamination of the Banning fault by Matti and Morton (1982) enlarged on Allen's studies by refining the geologic history and tectonic role of the fault zone.

Distribution and geologic setting

The Banning fault can be identified or inferred over a distance of about 100 km between the Indio Hills and the San Jacinto fault. The fault zone today consists of western, central, and eastern segments, each having a unique geologic and geomorphic setting and each recording a distinctive depositional and tectonic history during Quaternary time. These Quaternary events have obscured the distribution and history of an ancestral strike-slip fault that originally formed a single continuous trace throughout the three geographic segments.

Western segment.--The western segment of the Banning fault extends from the San Jacinto fault east to the Calimesa area. This segment has no surface expression because it is covered by late Pliocene and Quaternary sediments, and the position of the ancestral strand can only be inferred on the basis of gravity data (Willingham, 1971, 1981) and indirect geologic evidence.

Central segment.--The central, or San Gorgonio Pass, segment of the Banning fault extends from Calimesa to the vicinity of Whitewater Canyon. This segment largely is obscured by Quaternary sedimentary deposits, and has been modified by Quaternary reverse, thrust, and wrench faults of the San Gorgonio Pass fault zone. Where it crops out east of Calimesa and north of Banning, the Banning fault dips steeply to the north and juxtaposes crystalline rocks of San Gabriel Mountains-type against late Cenozoic sedimentary rocks; these exposures probably represent the ancestral trace of the fault. East of Banning, the ancestral trace is enmeshed in the San Gorgonio Pass fault zone and has been reactivated and obscured by Quaternary reverse and thrust faults of that system. For example, between Cabazon and Whitewater canyon, crystalline sheets have been thrust southward over the ancestral Banning fault and over Tertiary and Quaternary sedimentary deposits along low-angle fault surfaces that locally are flat or even south-dipping (Allen, 1957; D.M. Morton and J.C. Matti, unpublished data).

Eastern segment.--The eastern, or Coachella Valley, segment of the Banning fault extends from the vicinity of Whitewater canyon southeastward to the southern Indio Hills, where it merges with the San Andreas fault. The trace of the segment is well defined by conspicuous linear vegetation traces (Allen, 1957, fig. 1 of pl. 6) and forms degraded scarps in alluvial units that are late Pleistocene and Holocene in age. No published studies address the Quaternary history of this segment of the fault.

Geologic history

Late Cenozoic right-lateral history.--Evidence for at least 16 to 25 km of late Cenozoic right slip on the Banning fault is provided by geologic relations among Tertiary sedimentary rocks in the San Gorgonio Pass region. There, uppermost Miocene strata of the marine Imperial Formation south of the Banning fault have been displaced at least 11 km in a right-lateral sense from Imperial beds in the Whitewater area on the north side of the fault (Allen, 1957, p. 329). The 11-km separation is a minimum displacement, however, because the two sequences are not exact cross-fault counterparts: they differ in details of their physical stratigraphy and in their relations with underlying rocks. Moreover, their benthic foraminiferal assemblages suggest different paleogeographic settings for the two sequences (K. A. McDougall and J. C. Matti, unpublished data): Imperial beds south of the Banning fault represent a more offshore facies than beds north of the fault in the Whitewater area, which suggests that the southern sequence should be restored to a palinspastic position at least several kilometers farther offshore (southeast) from the more onshore Whitewater section.

In San Gorgonio Pass, the Painted Hill and Hathaway Formations (of Allen, 1957) provide additional evidence for right slip on the Banning fault. South of the fault, many conglomeratic beds in these units contain north-derived volcanic, plutonic, and gneissic clasts that could not have been derived from bedrock sources presently cropping out north of the fault (J. C. Matti and D. M. Morton, unpublished data). After about 140 km of right slip is restored on the Coachella Valley segment of the San Andreas fault (described above), restoration of 16 to 25 km of right slip on the Banning fault positions the Hathaway and Painted Hill Formations south of the southern Chocolate Mountains, where bedrock sources for some of their volcanic, plutonic, and metamorphic clasts can be found. However, the Hathaway Formation must have been deposited in a two-sided depositional basin having both northern and southern source areas because many of the unit's conglomeratic beds contain clasts of Peninsular Ranges-type from both lower and upper plates of the Eastern Peninsular Ranges mylonite belt (Matti and Morton, 1992).

Available evidence restricts right slip on the Banning fault to the late Miocene and earliest Pliocene. Displacements occurred after about 8 Ma because sedimentary and volcanic rocks displaced by the fault in San Gorgonio Pass are that age and younger (D. M. Morton, J. C. Matti, and J. L. Morton, unpublished data). Right slip occurred after about 7 Ma because the Banning fault has displaced the Imperial Formation 16 to 25 km and the unit appears to be about 7 m.y. old (Table 2). The late Miocene displacement episode may have extended into earliest Pliocene time, but recognition of Pliocene right slip on the Banning fault (if any) must await improved age control and facies analysis in the San Timoteo and Painted Hill Formations.

Quaternary history.--After the Banning fault was abandoned as a right-lateral strike-slip fault in earliest Pliocene time, the three segments of the fault had different geologic histories.

(1) The western segment did not generate ground ruptures of any kind during the Quaternary.

(2) The San Gorgonio Pass segment has been overprinted by compressional tectonism that created the San Gorgonio Pass fault complex--a later deformation that has been superimposed along the trend of the ancestral Banning fault but is not related kinematically to it.

(3) Unlike the western and central segments, the Coachella Valley segment has generated right-lateral displacements during Quaternary time. Paleocurrent directions and cobble compositions in Quaternary gravels of the eastern San Gorgonio Pass area indicate deposition by an ancestral Whitewater River; the clasts include a variety of bedrock stones of San Gabriel Mountains and San Bernardino Mountains type, and have southeasterly paleocurrents (J.C. Matti and B.F. Cox, unpubl. data). These data suggest that during late Quaternary time the gravels have been displaced about 2 to 3 km into San Gorgonio Pass by right slip on the Coachella Valley segment of the Banning fault (Sheet 2, F-F'). This figure probably represents the total amount of right slip on the segment since its Quaternary reactivation. Additional evidence for late Quaternary displacements on the Coachella Valley segment include right-laterally offset stream gullies cut into Pleistocene gravels between Whitewater Canyon and U.S. Highway 92 (Clark, 1984) and late Pleistocene gravel deposits in the Coachella Valley that may have been offset by the fault (Sheet 2, G-G'). The neotectonic trace of the segment probably correponds to the position occupied by the ancestral Banning/San Gabriel fault in late Miocene and early Pliocene time.

Although the age span for late Quaternary displacements has not been established, the Coachella Valley segment of the Banning fault probably has generated Holocene as well as late Pleistocene displacements. The fault appears to have been the source for the M=5.9 1986 North Palm Springs earthquake. However, although secondary ground failures developed in the vicinity of the surface trace of the Banning fault (Morton and others, 1989), the earthquake did not generate tectonic ground ruptures. The hypocenter for the 1986 event was located approximately halfway between Banning fault and the Coachella Valley segment of the San Andreas fault, and focal-plane solutions indicate reverse dip-slip as well as right-slip movements (Jones and others, 1988). If the 1986 earthquake originated on the Banning fault, the structure must dip moderately to the north beneath the Coachella Valley and may join the Coachella Valley segment of the San Andreas at depth.

Regional correlation.--Its late Miocene right-lateral history indicates that the ancestral Banning fault was a strand of the San Andreas transform system during the same period when the San Gabriel fault was an active component of the system. Many workers have proposed that the west end of the Banning fault has been displaced by the San Jacinto fault, and that its offset conterpart must continue to the west. Allen (1957, p. 339) may have been the first to suggest that the Banning is "the offset segment of one of the prominent east-west faults of the San Gabriel Mountains", but he did not cite the San Gabriel fault by name. Sharp (1967, p. 726) suggested that the Sierra Madre-Cucamonga fault may be the offset counterpart of the Banning fault, a view shared by Dibblee (1975a, p. 134).

We conclude that the San Gabriel and Banning faults originally formed a single throughgoing right-lateral fault, and suggest that the 22 km of right-lateral displacement suggested by Ehlig (1968a; 1975, p. 184) for the north branch of the San Gabriel fault corresponds to the 16 to 25 km of displacement we recognize for the Banning fault between 7.5 and 4 or 5 Ma. This right-slip activity would have coincided with latest Miocene displacements on the San Gabriel fault in Ridge Basin, where major right-lateral activity on the San Gabriel fault ceased about 5 m.y. ago (Crowell, 1982, p. 35, fig. 12). In the earliest Pliocene, the San Gabriel-Banning strand was bypassed by the San Andreas system as the San Andreas fault (*sensu stricto*) evolved to the east.

The Banning-San Gabriel connection via Neogene faults in the southeastern San Gabriel Mountains

Our conclusion that the Banning and San Gabriel faults once were continuous does not follow obviously from what is known about the two faults because (1) the north and south branches of the San Gabriel fault cannot be traced easily through and beyond the eastern San Gabriel Mountains, (2) the Banning fault cannot be traced easily west of the San Gorgonio Pass region, and (3) Quaternary right slip on the San Jacinto fault has rearranged and obscured any throughgoing connection between the two older faults.

Rocks and structures in the southeastern San Gabriel Mountains provide insight into possible relations between the San Gabriel and Banning faults. In the southeasternmost part of the range, two distinct suites of crystalline rock occur (fig. 3; Dibblee, 1968a, 1982a, figs. 1, 2; Morton, 1975a, fig. 1; especially see Ehlig, 1975, fig. 1, and 1981, fig. 10-2): (1) Pelona Schist and structurally overlying granitoid and gneissic rocks that respectively form lower and upper plates of the Vincent thrust, and (2) a suite of granitoid rocks and prebatholithic metasedimentary rocks of uncertain provincial affiliation. Lower- and upper-plate rocks of the Vincent thrust are typical of those elsewhere in the San Gabriel Mountains (Ehlig, 1975, fig. 1; 1981, fig. 10-2). However, granitoid and metasedimentary rocks in the southeasternmost part of the range have enigmatic provincial affinities and are structurally isolated from typical rocks of San Gabriel Mountains-type. The two suites evcrywhere are separated by high-angle faults (fig. 3): (1) on the east, the two suites are separated by northwest-trending right-lateral faults traditionally assigned to the San Jacinto[1] fault zone; (2) on the north, the two suites are separated by an east-trending zone of strike-slip faults referred to as the Icehouse Canyon fault; (3) on the west, the two suites are separated by the poorly studied Evey Canyon and San Antonio faults that traverse San Antonio Canyon (Ehlig, 1975, fig. 1; Morton, 1975a, figs. 1, 2; Dibblee, 1982a, fig. 1). We propose that these three fault zones and the granitic and metasedimentary terrane they enclose can be used to establish a connection between the San Gabriel and Banning faults.

Our correlation of the San Gabriel and Banning faults depends heavily on two inferences: (1) the enigmatic terrane of granitoid and metasedimentary rock in the southeastern San Gabriel Mountains is Peninsular Ranges-type rock that has been juxtaposed against San Gabriel Mountains-type rock (Matti and others, 1985; Matti and Morton, 1992), and (2) right-lateral displacement on a throughgoing San Gabriel-Banning fault contributed to this juxtapostion. In order to defend the San Gabriel-Banning connection we must defend these two propositions.

Provincial affinities.--Crystalline rocks enclosed by the "San Jacinto", Icehouse Canyon, and Evey Canyon faults are broadly similar to rocks of Peninsular Ranges-type. The granitoid rocks consist mainly of foliated biotite-hornblende quartz diorite and tonalite (Ehlig, 1975, 1981; Morton, 1975a; Evans, 1982; Morton and others, 1983; Morton and Matti, 1987, Plate 12.1, rock units Kqd and Kd; May and Walker, 1989) that locally are intruded by small bodies of monzogranite and garnetiferous muscovite-bearing monzogranite (Morton and Matti, 1987, Plate 12.1, unit Kqm). These granitoids probably all are Cretaceous, although emplacement ages of about 87 Ma (May and Walker, 1989) have been moderately to strongly reset by an early Tertiary thermal event (Miller and Morton, 1980). The quartz dioritic and tonalitic rocks are progressively more deformed southward toward the San Gabriel Mountain front, culminating in an east-trending zone of mylonite and mylonitic quartz diorite first studied by Alf (1948) and Hsu (1955) and later mapped by Morton (1975a, 1976; Morton and others, 1983; Morton and Matti, 1987, Plate 12.1). At the mountain front, crystalline rocks structurally beneath the mylonite belt consist of multiply-deformed gneiss, quartz diorite, and garnetiferous hypersthene-bearing retrograded granulite rocks. Most workers assign a Precambrian age to these deformed rocks based on their unique structural and metamorphic history, but Ehlig (1975, fig. 1; 1981, fig. 10-2) believed them to be younger and grouped them with other granitoid rocks in this part of the southeastern San Gabriel Mountains that he inferred to be Mesozoic in age. Granulite-facies metamorphism appears to be early Cretaceous in age on the basis of a 108-Ma U-Pb age obtained by May and Walker (1989) from a late-stage syntectonic pyroxene-plagioclase pegmatite associated with the retrograded granulite rocks.

Prebatholithic metasedimentary rocks intruded by the granitoids consist of amphibolite-grade marble, metaquartzite, and pelitic gneiss and schist that locally is graphitic. North of the main mylonite belt the metasedimentary rocks occur as large bodies and pendants; south of the mylonite belt the metasedimentary rocks occur only as thin septa and xenoliths. Most workers assign a late Proterozoic or early Paleozoic age to the sedimentary protoliths based on their general similarities to rocks known to be that age elsewhere in southern California.

Matti and others (1985, p. 3) speculated that the crystalline terrane enclosed by the "San Jacinto", Icehouse Canyon, and Evey Canyon faults is part of the Peninsular Ranges block. We reiterate this proposal here, and support it with several lines of evidence:

(1) Quartz diorite and tonalite in the southeasternmost San Gabriel Mountains are similar to quartz diorite and tonalite in the northeastern Peninsular Ranges block: the granitoids appear to have similar intrusive ages that have been reset by a younger thermal event (Miller and Morton, 1980, and unpublished K/Ar data), and they have similar major and minor element compositions (Baird and others, 1974, 1979).

(2) The mylonitic belt of ductile deformation that separates foliated granitoid rocks from highly deformed retrograded granulites in the San Gabriel Mountains is similar to the Eastern Peninsular Ranges mylonite zone of Sharp (1979), except that mylonitic lineations are oriented down-dip in most parts of the Eastern Peninsular Ranges mylonite zone (Erskine, 1985) but are oriented parallel to strike in the San Gabriel Mountains (Morton and Matti, 1987; May and Walker, 1989). This discrepancy could reflect either spatial differences in the orientation of the syntectonic strain field within the regionwide mylonite belt (May and Walker, 1989) or localized post-tectonic rotation of the mylonite fabrics around vertical and/or horizontal axes. Other workers have

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[1]Because of confusion between Quaternary displacements [if any] and older displacements within the San Jacinto fault zone in the southeastern San Gabriel Mountains, we use the term "San Jacinto fault" to refer to Miocene displacements.

pointed out similarities between the two mylonite belts (Hsu, 1955; Ehlig, 1975, p. 183; Erskine, 1985).

(3) Bodies of garnetiferous muscovite monzogranite structurally overlying the mylonite belt in the southeastern San Gabriel Mountains (Morton and Matti, 1987, Plate 12.1, units Kg and Kgc) are comparable to similar bodies structurally above and beneath the Eastern Peninsular Ranges Mylonite Belt in the Santa Rosa Mountains (Matti and others, 1983b, unit Mzlm).

(4) Prebatholithic metasedimentary rocks in the southeasternmost San Gabriel Mountains are broadly similar to metasedimentary rocks structurally above and beneath the mylonite belt in the San Jacinto and Santa Rosa Mountains (Powell, 1982a; Matti and others, 1983b, units gsc, mq, and mc; Erskine, 1985). Powell (1982a) has grouped these and similar prebatholithic metasedimentary rocks into his Placerita terrane.

Correlation of faults.--If the enigmatic granitoid and metasedimentary rocks in the southeastern San Gabriel Mountains are rocks of Peninsular Ranges-type, then their present tectonic juxtaposition against rocks of San Gabriel Mountains-type must be explained by identifiable structures--ductile, brittle, or both. May and Walker (1989) proposed that the enigmatic suite (their Cucamonga and San Antonio terranes) was juxtaposed against rocks of San Gabriel Mountains-type in late Cretaceous or early Paleogene time by ductile oblique left-lateral convergence within a mylonite zone locally preserved along the boundary between the two terranes (May, 1990). Regional telescoping along Cretaceous or Paleogene ductile zones may well account for the primary structural geometry between the two crystalline terranes. However, we propose that their *present* juxtaposition in the San Gabriel Mountains resulted from brittle displacements on throughgoing Neogene faults whose dismembered segments now are represented by the "San Jacinto", Icehouse Canyon, and Evey Canyon faults.

If these three faults are Neogene, and once were continuous with other Neogene strike-slip faults in southern California, then their regional counterparts should be nearby and should have a similar relationship to rocks of San Gabriel Mountains-type and Peninsular Ranges-type. One candidate is the Banning fault, which in the San Gorgonio Pass region intervenes between rocks of San Gabriel Mountains-type to the north and rocks of Peninsular Ranges-type to the south. Likewise, in the southeastern San Gabriel Mountains, the "San Jacinto" and Icehouse Canyon faults intervene between rocks of San Gabriel Mountains-type to the north and east and rocks we identify as Peninsular Ranges-type to the south (fig. 3). The structural position occupied by the "San Jacinto" and Icehouse Canyon faults thus is similar to that of the Banning fault (fig. 3, map sheets 1 and 2). We use this relation as a primary basis for our proposal that the Banning, "San Jacinto", and Icehouse Canyon faults once were continuous and shared common movement histories.

We complete the San Gabriel-Banning connection by projecting the Banning-"San Jacinto"-Icehouse Canyon trend westward beyond San Antonio Canyon. A likely candidate for this continuation is the east-oriented north branch of the San Gabriel fault--a structure that has about 22 km of late Miocene right slip (Ehlig, 1973, 1975, 1981) that compares well with 16 to 25 km of late Miocene right slip on the Banning fault in San Gorgonio Pass. Similarities in their movement histories suggest that the faults are related, and we propose that they once formed a single throughgoing right-lateral trend that since has been disrupted by about 25 km of Quaternary right slip on the "San Jacinto fault" and about 3 km of Quaternary left slip on the San Antonio fault. The former has displaced the east end of the Icehouse Canyon fault from the Banning fault; the latter has displaced the west end of the Icehouse Canyon fault from the north branch of the San Gabriel fault (fig. 3).

This scenario provides a connection between the north branch of the San Gabriel fault and the Banning fault but leaves unresolved the connection (if any) between the south branch of the San Gabriel fault and the Banning. Most workers follow Crowell (1975a,b, 1981, 1982) and Ehlig (1975, 1981) who convey 38 km of right slip on the south branch eastward toward the San Andreas or Banning faults by way of connecting faults in the southeastern San Gabriel Mountains (Dibblee, 1968a, fig. 1; Ehlig, 1973, fig. 1 and 1981, fig. 10-2; Crowell, 1975a, fig. 1, 1975c, p. 208-209, 1982a, fig. 1). To these scenarios we add one in which the San Gabriel fault (south branch) traverses the south front of the San Gabriel Mountains, is displaced about 3 km left laterally by the San Antonio fault, and continues east to the "San Jacinto fault" by way of the Stoddard Canyon fault and thence to the Banning fault (fig. 3).

As developed to this point, our model for the San Gabriel-Banning connection accomodates three concerns: (1) it accounts for two of the three Neogene faults in the southeastern San Gabriel Mountains that separate Peninsular Ranges-type rock from San Gabriel Mountains-type rock; (2) it ties together similar right-slip histories on the San Gabriel fault (north branch) and the Banning fault; and (3) it provides a testable hypothesis for a connection between the San Gabriel fault (south branch) and the Banning fault. This model also provides a testable solution for two other problems: the amount of right slip on the San Gabriel fault (south branch) and the regional distribution of the left-lateral Malibu Coast fault zone. We propose that a solution to both problems is provided by the Evey Canyon fault--the third Neogene fault in the southeastern San Gabriel Mountains that juxtaposes rocks of Peninsular Ranges-type and San Gabriel Mountains-type.

Pivotal to this analysis is the regional distribution and tectonic role of the Malibu Coast-Santa Monica-Raymond fault zone--a major left-lateral fault that trends easterly from the California coast to the south-frontal fault zone of the San Gabriel Mountains. Barbat (1958, fig. 2, p. 64) originally suggested that the Santa Monica segment of the zone generated about 13 km of left slip. Subsequently, Yeats (1968), Yerkes and Campbell (1971), Jahns (1973), Campbell and Yerkes (1976), and Truex (1976) presented evidence for 60 to 90 km of left slip on the Malibu Coast-Santa Monica-Raymond trend during the middle Miocene (about 16 Ma to 12 Ma). Based on the premise that a left-lateral fault of this scale must be of regional extent, these workers extended the Malibu Coast-Raymond system eastward through the Cucamonga fault zone (Barbat, 1958, fig. 1; Jahns, 1973, fig. 5; Campbell and Yerkes, 1976, fig. 1) and ultimately through San Gorgonio Pass by way of the Banning fault (Jahns, 1973, fig. 6-9, p. 166).

We accept the premise that the Malibu Coast-Santa Monica-Raymond fault is a major left-lateral structure that should be recognizable east of the frontal-fault zone of the San Gabriel Mountains. However, rather than merge the Malibu Coast system with the frontal fault zone and extend it east through the Cucamonga fault, we suggest that the Malibu

Coast system may have been truncated by the south branch of the San Gabriel fault and displaced right laterally from a cross-fault counterpart located to the east. We propose that the Evey Canyon fault is the displaced continuation of the Malibu Coast-Santa Monica-Raymond trend, which requires that the Evey Canyon is a left-lateral fault that juxtaposed Peninsular Ranges-type rocks against San Gabriel Mountains-type rocks (fig. 3; Matti and others, 1985). The once continuous middle Miocene Malibu Coast-Santa Monica-Raymond-Evey Canyon fault was truncated in late Miocene time by the San Gabriel fault (south branch), which has displaced the southwest end of the Evey Canyon fault about 22 km from the east end of the Raymond fault. This forms the basis for our displacement estimate of 22 km for the south branch, and underlies our conclusion that the San Gabriel fault (north and south branches) has no more than 44 km of right slip (22 km + 22 km).

Our conclusion that the Evey Canyon fault is a left-lateral structure that once was part of the Malibu Coast system has implications for the Icehouse Canyon, "San Jacinto", and Banning faults. The northeast end of the Evey Canyon fault terminates against the north-trending San Antonio fault, a structure that has displaced the north and south branches of the San Gabriel fault about 3 km from their inferred cross-fault counterparts (the Icehouse Canyon and Stoddard Canyon faults, respectively; fig. 3). Oblique convergence between the Evey Canyon and San Antonio faults precludes accurate determination of their geometric relations, and it is likely that left slip on the north-trending San Antonio fault has occurred by reactivation of north-trending segments of the Evey Canyon fault. Despite these complications, we propose that restoration of 3 km of left slip on the San Antonio fault would align the northeast end of the Evey Canyon fault with the Icehouse Canyon fault, which thereby is potentially continuous with the left-lateral Malibu Coast-Evey Canyon trend.

This implication appears to be at odds with our proposal that the Icehouse Canyon fault is a right-lateral component of the San Gabriel-Banning connection--a contradiction that becomes more profound if large left-lateral displacements proposed for the Malibu Coast-Raymond system are projected east along an Evey Canyon-Icehouse Canyon-"San Jacinto" trend that ultimately includes the Banning fault. This apparent contradiction can be resolved in two ways:

First, fault zones established initially by middle Miocene left slip within a throughgoing Malibu Coast-Santa Monica-Raymond-Evey Canyon-Icehouse Canyon-"San Jacinto"-Banning trend could have been reactivated as zones of late Miocene right slip when the Banning-"San Jacinto"-Icehouse Canyon segment of the Malibu Coast system was incorporated into the San Gabriel-Banning system (a concept suggested to us generically by T.H. McCulloh).

Second, May and Walker (1989, p. 1262-1263) suggested that kinematic models for tectonic rotations in southern California (Luyendyk and others, 1980; Hornafius and others, 1986) require that left slip on the Malibu Coast-Raymond system should decrease to the east, thereby eliminating the need to extend large left-lateral displacements throughout the entire length of the Malibu Coast system. May and Walker (1989) adopted our earlier suggestion (Matti and others, 1985) that the Evey Canyon fault is part of the Malibu Coast system, but suggest that large left-lateral displacements (60 to 90 km) proposed for western segments of the Malibu Coast-Evey Canyon system diminish to about 20 km in the southeastern San Gabriel Mountains. By this interpretation, left slip may not be significant on the Icehouse Canyon-"San Jacinto"-Banning segment of the Malibu Coast system, and may not even have extended all the way east on the Banning fault. This would obviate the need to extend large displacements on the Malibu Coast system east through San Gorgonio Pass (Jahns, 1973), and would fit the lack of evidence for Neogene left slip on the Banning fault.

We cannot resolve uncertainties involving the regional distribution of the middle Miocene Malibu Coast system. However, rather than arbitrarily ending the Malibu Coast-Santa Monica-Raymond system at the northeast end of the Evey Canyon fault, we incorporate modest left slip on the Evey Canyon-Icehouse Canyon-Banning segment of the Malibu Coast system. We estimate this left slip to be about 25 km based on our speculation that the Eastern Peninsular Ranges mylonite zone in the southeastern San Gabriel Mountains has been displaced about 25 km from a possible cross-fault counterpart buried beneath Neogene and Quaternary sedimentary rocks between the Santa Monica Mountains and Verdugo Hills.

Summary.--In the southeastern San Gabriel Mountains and San Gorgonio Pass region, several strike-slip faults traverse the boundary zone between rocks of Peninsular Ranges-type and San Gabriel Mountains-type. Our interpretation of movement histories for these faults requires that they are local segments of regionwide strike-slip fault trends that include (1) the middle Miocene Malibu Coast-Santa Monica-Raymond-Evey Canyon-Icehouse Canyon-"San Jacinto"-Banning left-lateral system and (2) the late Miocene San Gabriel-Icehouse Canyon-Stoddard Canyon-"San Jacinto"-Banning right-lateral system. The Malibu Coast-Banning system produced about 25 km of left slip in middle Miocene time (14 to about 12 Ma). In late Miocene time (about 10 Ma), the Malibu Coast-Banning left-lateral system was dismembered and locally reactivated by displacements within the right-lateral San Gabriel-Banning system.

During late Miocene time the San Gabriel-Banning fault formed a single, throughgoing right-lateral structure that was part of the San Andreas transform system. The middle segment of this throughgoing structure, now located in the San Gabriel Mountains, developed two discrete strands that probably formed sequentially. To the northwest, these two strands coalesced to form a single strand (the San Gabriel fault) that traverses the west margin of Ridge Basin; to the southeast, the two strands coalesced to form a single strand (the Banning fault) that traverses the San Bernardino Valley, San Gorgonio Pass, and Salton Trough. Within the southeastern San Gabriel Mountains, remnants of the two San Gabriel-Banning fault strands are represented by the Stoddard Canyon, Icehouse Canyon, and "San Jacinto" faults.

The throughgoing San Gabriel-Banning system generated about 44 km of right-lateral displacement in late Miocene to earliest Pliocene time (10 to 4 or 5 Ma). The south branch of the San Gabriel fault probably is the older fault strand, and we propose that from about 10 Ma to about 7.5 Ma it generated about 22 km of displacement that displaced the Evey Canyon fault from the Raymond fault. This displacement must have extended along the Banning fault, but rocks of this age that would record right-lateral movements from 10 Ma to 8 Ma are not exposed in San Gorgonio Pass. If the San Gabriel-Banning fault gradually was bowed into a convex-west arc during this early history, the curvature ultimately could have become too extreme to have accommodated efficient right-slip displacements. We propose that this happened about 7.5 m.y. ago, at which time the south branch was abandoned and right slip stepped inboard (east) to the north branch. From about 7.5 Ma to about 4 or 5 Ma the north branch generated 22 km of displacement (Ehlig, 1973, p. 174)--a displacement recorded by upper Miocene sedimentary and volcanic rocks that are traversed by the Banning fault in San Gorgonio Pass. According to this model, total right slip on the combined north and south branches of the San Gabriel-Banning fault is about 44 km--16 km short of the 60 km proposed by Crowell (1982a) and by Ehlig and Crowell (1982). Major right-lateral activity on the throughgoing fault ceased about 4 or 5 m.y. ago (Crowell, 1982a, p. 35, fig. 12) as the San Gabriel-Banning strand was bypassed by the San Andreas system and as strands of the San Andreas fault proper evolved to the east.

COMPRESSIONAL FAULT SYSTEMS

SAN GORGONIO PASS FAULT ZONE

We apply the name San Gorgonio Pass fault zone to a series of Quaternary reverse, thrust, and wrench faults that extends from the Whitewater area westward to the Calimesa area. This system is associated spatially with the Banning fault, but the evolution of the San Gorgonio Pass fault zone has no relationship kinematically to the paleotectonic Banning fault. The following discussion is based on unpublished mapping still in progress.

In map view, the San Gorgonio Pass fault zone has a distinctive zig-zag character caused by repetition of a distinctive fault geometry--an L-shaped fault distribution in which the elongate staff of the L is oriented northwestward and the shorter base of the L eastward to northeastward. The east-oriented segments are reverse and thrust faults, with moderately dipping reverse faults in the west half of the fault zone and shallowly dipping thrust faults in the east half. The northwest-oriented segments appear to be vertical wrench faults having oblique right-lateral displacements. These segments have approximately the same orientation as active right-lateral faults in the region.

On the east, faults of the San Gorgonio Pass zone first appear a few km west of Whitewater River, where the Coachella Valley segment of the Banning fault splays into multiple north-dipping thrust sheets (Morton and others, 1987). Traced westward, faults of the San Gorgonio Pass zone disappear in the Calimesa area--a region where we identify normal faults of the Crafton Hills horst-and-graben complex and where the San Bernardino strand of the San Andreas fault changes to a more northerly strike. These spatial relations between neotectonic fault complexes having three different kinematic styles (right-lateral strike slip, extension, and contraction) suggest that the fault systems are mechanically interelated.

Faults of the San Gorgonio Pass zone all are late Quaternary in age. Some faults in the complex may have been active only in late Pleistocene time; others have been active throughout the late Pleistocene and Holocene and have generated ground ruptures as recently as a few thousand years ago (J.C. Tinsley and J.C. Matti, unpubl. trench data, 1986). Faults with confirmed Holocene displacements have been identified only in the eastern part of the San Gorgonio Pass zone between Beaumont and Whitewater; faults in the western part of the zone between Beaumont and Calimesa appear to have been active only in late Pleistocene time (J.C. Matti and D.M. Morton, unpubl. data). However, future ground ruptures throughout the entire extent of the San Gorgonio Pass fault zone cannot be ruled out.

CUCAMONGA FAULT ZONE

The Cucamonga fault is a zone of Quaternary reverse and thrust faults that separates crystalline rocks of the San Gabriel Mountains from alluviated lowlands of the upper Santa Ana River valley (Morton, 1975a,b, 1976; Morton and Matti, 1987). The pre-Quaternary history of the Cucamonga fault is obscure, but its latest Pleistocene and Holocene history reflects convergence between the Perris block and the San Gabriel Mountains (Morton and Yerkes, 1974; Morton and others, 1982; Morton and Matti, 1987).

Faulting within the Cucamonga fault zone has recurred episodically during Quaternary time. The oldest faults occur within the north part of the fault zone, where some faults cut crystalline basement rock but do not break even the oldest Quaternary alluvial units. Younger faults occur farther south at the mountain front and form conspicuous scarps in young Pleistocene and Holocene alluvial fans (Morton and Matti, 1987). These relations suggest that during late Pleistocene and Holocene time, faulting within the Cucamonga fault zone migrated southward. This southward-younging pattern is complicated by merging of individual strands locally and by apparent merging of all strands in the western part of the fault zone. Latest episodes of strain release may have occurred mainly in the eastern 15 km of the fault zone and not throughout its entire 25-km length. The more complicated fault pattern in the eastern part of the zone may reflect interaction between the Cucamonga and San Jacinto faults. We speculate that northwestward migration of the Perris block by right-lateral strike-slip on the San Jacinto fault during the Quaternary has been taken up partly by reverse and thrust-fault displacements within the Cucamonga fault zone.

EXTENSIONAL FAULT SYSTEMS

NORMAL FAULTS OF THE COACHELLA AND MORONGO VALLEYS

Faults that have normal dip-slip separations occur in the southern Indio Hills and in the northern Coachella Valley. Clark (1984, p. 4-5, map sheet 1) attributed the distinctive zone of normal faults in the southern Indio Hills to uplift northeast of the San Andreas fault, which he in turn related to displacements across the San Andreas. Northeast-oriented faults in the northern Coachella Valley have not been studied; the faults have both north- and south-facing scarps, and break late (but not latest) Quaternary alluvium. Northeast-oriented faults and lineaments in the Morongo Valley area, including the Morongo Valley fault, also appear to have normal dip-slip separations. The kinematic role of normal faults in this region has not been documented.

BEAUMONT PLAIN FAULT ZONE

We apply the name Beaumont Plain fault zone to a series of northwest-trending en-echelon fault scarps that traverse late Quaternary alluvial deposits in the vicinity of Beaumont. Most of the scarps face northeast, but one short scarp segment faces southwest. We have not documented the style or history of faulting that created these scarps; however, they appear to have formed by normal dip-slip displacements and probably represent an extensional strain field. This interpretation is strengthened by closely spaced northeast- and southwest-facing scarps northeast of Beaumont which bound a downdropped block that forms a graben. Similar faults having northwest trends and northeast-facing scarps occur elsewhere in the San Gorgonio Pass region--for example, scarps that have been referred to the modern trace of the San Andreas fault at Burro Flat, and scarps near Oak Glen and Wildwood Canyon. We do not understand the kinematic role of these faults, but they may represent a family of related features formed by regional extension.

CRAFTON HILLS HORST-AND-GRABEN COMPLEX

We apply the name Crafton Hills fault zone to a system of normal dip-slip faults that forms a horst-and-graben complex in the vicinity of Redlands and Yucaipa. These faults bound the west and east flanks of the Crafton Hills, and break late Quaternary alluvium in the valleys of Oak Glen and Wilson Creeks. The faults trend northeast in the vicinity of the Crafton Hills (Matti and others, 1992), but adopt more easterly trends near the San Bernardino strand of the San Andreas fault and south of Redlands (Morton, 1978b). Normal faulting within this zone coincides geographically with a series of conspicuous left steps in the San Bernardino strand, and with the western termination of the San Gorgonio Pass compressional fault system.

The Crafton Hills horst-and-graben complex is a neotectonic structural element that has been active during both late Pleistocene and Holocene time, although not all faults in the zone break Holocene alluvial deposits. The complex represents a zone of extensional faulting in a region where right-lateral and reverse faulting are the most obvious expressions of crustal deformation.

DIP-SLIP FAULTS OF THE SAN BERNARDINO VALLEY AND SAN BERNARDINO MOUNTAINS

The Peters and Tokay Hill faults occur south of the San Bernardino strand of the San Andreas fault in the Devore area southeast of Cajon Pass (Morton and Miller, 1975; Morton and Matti, 1990b). The faults break Holocene deposits and probably have normal dip-slip displacements. This geometry is complicated locally where the Tokay Hill fault intersects the San Bernardino strand of the San Andreas fault: there, the Tokay Hill fault dips southwest and appears to have a reverse dip-slip geometry (relations observed by us in a trench excavated by G. Rasmussen and Associates). Similar faults traverse the southwest-facing escarpment of the western San Bernardino Mountains; they are east-trending, and almost all have north-facing scarps with down-on-the-north displacements (Weldon, 1985b, pl. 12). The Peters and Tokay Hill faults and those in the western part of the San Bernardino Mountains form a family of related dip-slip faults that reflect an extensional strain field.

NEOTECTONIC FRAMEWORK OF THE SOUTH-CENTRAL TRANSVERSE RANGES AND VICINITY

Seismicity, strain, and slip rates

Seismicity

Early studies of seismicity in the vicinity of the south-central Transverse Ranges were published by Dehlinger (1952), Richter and others (1958), Allen and others (1965), Brune and Allen (1967), Cheatum and Combs (1973), Hadley and Combs (1974), Thatcher and others (1975), and Fuis and Lamanuzzi (1978). Recent studies have been conducted by Green (1983), Nicholson and others (1983, 1984a, b, 1986), Williams and others (1984), Corbett and Hearn (1984), Sanders and Kanamori (1984), Webb and Kanamori (1985), Jones (1988), and Jones and others (1988).

Richter and others (1958) evaluated the 1948 Desert Hot Springs earthquake (M_L=6.5), which they attributed to the Coachella Valley segment of the San Andreas fault (their Mission Creek fault). However, epicenters for this earthquake and for associated shocks did not align with the surface trace of the fault but instead formed a lineamint parallel to and several kilometers north-northeast of the trace, and surface ruptures were not reported for the earthquakes. First-motion studies for the 1948 earthquake suggest oblique right-lateral displacement having a thrust component along a fault plane dipping northeast (Allen, 1957, p. 342; Richter and others, 1958). Thus, it is unclear if the 1948 earthquake sequence can be attributed to the Coachella Valley segment.

Allen and others (1965) evaluated the seismicity of the southern California region, including the south-central Transverse Ranges and vicinity, and concluded that although seismicity patterns were consistent with some of the major fault systems, much of the seismicity is diffuse and is not associated with known faults. Brune and Allen (1967) and later workers have emphasized this conclusion with regard to the San Andreas fault system.

Comprehensive analysis of focal mechanisms and hypocentral plots in the south-central Transverse Ranges and vicinity refined the results of earlier studies and offered several new conclusions (Green, 1983; Jones, 1988). (1) Seismicity is not associated with strands of the San Andreas fault (also see Allen and others, 1965; Brune and Allen, 1967; Nicholson and others, 1983). (2) A deep wedge of seismicity in San Gorgonio Pass yields reverse and thrust mechanisms but includes left-lateral and right-lateral mechanisms, and defines the deepest seismicity known from southern California (22 km; also see Fuis and Lamanuzzi, 1978; Nicholson and others, 1983, 1986; Corbett and Hearn, 1984; Webb and Kanamori, 1985). This wedge is bounded on the north by the Mission Creek fault, on the west by the Banning Canyon - Burro Flat segment of the San Bernardino strand of the San Andreas, on the south by the Banning fault, and on the east by a transitional boundary with an area of low seismicity in the northern Coachella Valley. (3) Pure dip-slip mechanisms and oblique dip-slip mechanisms with a left-lateral component occur in the vicinity of the Crafton Hills horst-and-graben complex (also see Nicholson and others, 1983, 1986), and normal mechanisms occur locally within the San Bernardino valley region (Jones, 1988; also see Webb and Kanamori, 1985, fig. 5a). (4) Left-lateral mechanisms appear to define northeast-oriented seismicity lineaments that traverse the San Bernardino valley region (also see Nicholson and others, 1983, 1986). (5) No seismicity is associated with the Coachella Valley segments of the San Andreas and Banning faults.

In contrast to the San Andreas fault, active seismicity is associated with the trace of the San Jacinto fault, which in the vicinity of the south-central Transeverse Ranges has generated at least three historic earthquakes of magnitude (M_L) 6 or greater. Two of these occurred in the southern San Jacinto Valley (Sanders and Kanamori, 1984, p. 5874-5875, fig. 2; note slight differences in epicentral position compared to Thatcher and others, 1975, fig. 1); the third probably occurred near Loma Linda on either the San Jacinto fault or the nearby Loma Linda fault (Sanders and Kanamori, 1984, p. 5873-5874, fig. 2). Both macro- and microseismicity define relatively quiet and active segments of the fault. For example, rates of microseismicity are relatively high in the southern part of the San Jacinto Valley but are significantly lower in the Reche Canyon area (Brune and Allen, 1967, locs. 13 and 37 of Table 1 and fig. 3; Cheatum and Combs, 1973, p. 5). Green (1983, pl 1) indicates that microseismicity is low along the San Jacinto fault between Reche Canyon and Cajon Pass, but she reported a dense cluster of seismicity presumably associated with the Loma Linda fault 2 km east of the San Jacinto fault near Loma Linda. This cluster is associated with the convex-west bow in the regional strike of the San Jacinto fault. Thatcher and others (1975) used macroseismicity patterns to suggest that a gap in seismic slip occurs on the San Jacinto fault between Reche Canyon and the Cajon Pass region.

Slip rates

San Andreas fault, Coachella Valley segment.--Studies by Keller and others (1982) in the southern Indio Hills indicate that the Coachella Valley segment of the San Andreas fault (their Mission Creek fault) has late Quaternary slip rates of between 10 and 35 mm/year, with a best estimate of 25 to 35 mm/year; this rate presumably applies to the Holocene as well as the late Pleistocene. During late Pleistocene time, this amount of slip probably carried up the Coachella Valley segment and through the San Bernardino Mountains on the Mill Creek fault. However, as discussed below, during Holocene time the 25- to 35-mm rate may have carried no farther northwest than the vicinity of Desert Hot Springs.

San Gorgonio Pass fault zone.--Ongoing studies by the U.S. Geological Survey (J.C. Tinsley and J.C. Matti, unpubl. data) indicate that the strain budget for thrust faults of the San Gorgonio Pass zone may be quite complex. A thrust-fault scarp trenched on the Millard Canyon fan disrupts young alluvial deposits along fault planes that dips north at less than 20°. Preliminary age determinations from detrital charcoal suggest that some of the faulted deposits may be as young as 2,850 to 3,600 yr (^{14}C ages uncorrected). An intense scarp-building period during the early part of this period was followed by a period during which only one scarp-forming event may have occurred in the last 2,850 years. These data suggest that modern seismicity patterns may be spatially and temporally cyclic, with high-strain periods followed by low-strain periods.

San Jacinto fault.---Sharp (1981) indicates a minimum Quaternary long-term slip rate of about 8 to 12 mm/year for the fault in the vicinity of Anza. South of metropolitan San Bernardino, Wesnousky and others (1991; Prentice and others, 1986) determined a minimum slip rate of 1.7 to 3.3 mm/yr for the San Jacinto fault, although their studies did not capture all strands of the San Jacinto zone. Prentice and others (1986) propose that the long-term Quaternary slip rate on the northern San Jacinto fault probably averages about 10 mm/yr. However, Morton and others (1986) discuss San Bernardino Mountains-derived clast populations in Pleistocene deposits of the San Timoteo Badlands that may require accelerated long-term slip on the San Jacinto fault--particularly during geologic intervals when strands of the San Andreas fault in the San Bernardino Mountains region were tied up within the San Gorgonio Pass structural knot.

San Andreas fault, San Bernardino strand.--In the Cajon Pass region the San Bernardino strand has a Holocene slip rate of about 25 mm/year (Weldon and Sieh, 1985). Rasmussen (1982) indicates a similar rate farther southeast in the vicinity of Highland.

The San Bernardino strand southeast of Santa Ana River may have a variable slip-rate history that reflects the complex geologic evolution of the strand. In order to determine long-term slip rates for the fault at its southeast extent, Harden and Matti (1989) examined soil profiles of alluvial units in the Yucaipa area that contain clast populations derived from various distinctive bedrock units that crop out on Yucaipa Ridge. Throughout Holocene and latest Pleistocene time these alluvial-fan units have been displaced right-laterally away from their source areas. Within the limits of uncertainty posed by the soils data and by ambiguities in the displacement paths of the alluvial-fan deposits, Harden and Matti (1989) reached two main conclusions: (1) Holcene slip rates on the San Bernardino strand here approach the 25 mm/yr rates proposed for the fault in the Cajon Pass region (Weldon and Sieh, 1985; McFadden and Weldon, 1987); and (2) late Pleistocene slip rates appear to be considerably lower than Holocene rates, on the order of 6 to 13 mm/yr. These conclusions suggest that long-term slip on the San Bernardino strand has accelerated with time. We believe that this slip-rate scenario is compatible with gradual inception of the San Bernardino strand by reactivation of the abandoned Mission Creek strand starting in late Pleistocene time (discussed above).

Cucamonga fault zone.--The Cucamonga fault zone at Day Canyon in the east-central part of the zone has a minimum convergence rate of about 5 mm/year for the last 13,000 years (J.C. Matti, D.M. Morton, J.C. Tinsley, and L.D. McFadden, unpubl. data). Age control for this determination is based on correlation of pedogenic soils that cap faulted alluvial deposits; the faulted deposits could be younger (but probably not older), in which case the convergence rate would be greater. Matti and coworkers conclude that earthquakes with vertical displacements of about 2 m had an average recurrence of about 625 years. Seismic-moment calculations indicate expectable surface-wave magnitudes (M_S) of 6.9 to 7.2 for fault-rupture lengths of 10 to 25 km.

Strain

Trilateration measurements in the Salton Trough indicate that the Coachella Valley segment of the San Andreas fault is accumulating strain at a rate of about 25 mm/year (Savage and others, 1979, table 3; King and Savage, 1983; Savage, 1983, figs. 2, 3). Line-length measurements by Savage and Prescott (1967) across a doubly braced quadrilateral spanning the San Jacinto fault in the San Jacinto Valley indicate that 25 mm/year of right-lateral shear strain is accumulating across the fault, assuming it is locked to depths of 20 km; this rate contrasts with a minimum long-term Quaternary rate of 8 to 12 mm/year determined by Sharp (1981) from geologic data further to the southeast.

Neotectonic framework

Most of the neotectonic elements in the vicinity of the south-central Transverse Ranges occur within or adjacent to San Gorgonio Pass--a structural knot in the modern San Andreas fault. We propose that many of these fault complexes owe their origin and kinematics to this structural knot.

The San Gorgonio Pass knot lies between the Coachella Valley and Mojave Desert segments of the San Andreas fault. Both segments approach the knot in a straightforward manner, but as Allen (1957, p. 337-339) originally demonstrated, neotectonic strands of these faults cannot be traced as continuous features through the San Gorgonio Pass region. Similar difficulties exist for the Coachella Valley segment of the Banning fault: the regional strike of this strand is aligned with the San Bernardino strand of the San Andreas fault, suggesting a geometric and kinematic relation between the two faults, but Allen (1957) showed that Quaternary thrust and reverse faults in San Gorgonio Pass obscure relations between them. Allen (1957, p. 337) explored five ways that the modern San Andreas might pass through the San Gorgonio Pass knot, of which three are major possibilities:

(1) The aligned San Bernardino strand and Coachella Valley segment of the Banning fault once formed a straight throughgoing trace within the San Gorgonio Pass region, but this trace subsequently has been deflected into a sharp bend that has created the San Gorgonio Pass knot. This interpretation is favored by Dibblee (1968; 1975a, p. 134; 1982, p. 166).

(2) The aligned San Bernardino strand and Coachella Valley segment of the Banning fault may form a straight throughgoing trace within the San Gorgonio Pass region, but this trace is concealed beneath a major thrust sheet of crystalline rock. This interpretation requires that right-slip occurs beneath the thrust plate and that the two strike-slip faults plunge beneath the thrust sheets as they approach San Gorgonio Pass from the northwest and southeast, respectively. Although such a relation can be mapped where the Coachella Valley segment of the Banning fault enters San Gorgonio Pass, similar relations have not been demonstrated for the San Bernardino strand where it would have to plunge southeastward beneath the thrust sheet.

(3) The San Bernardino strand and Coachella Valley segment of the Banning fault may be aligned and may interact kinematically, but the two strands never had a throughgoing connection. Thus, the San Bernardino strand dies out as it approaches San Gorgonio Pass, and neotectonic displacements on the Banning fault have been taken up by compressional convergence in the Pass region. Allen (1957, p. 338-339) favored this interpretation, and we concur.

The fact that none of the neotectonic right-lateral faults of the Coachella Valley can be traced northwestward through the greater San Gorgonio Pass re gion raises a major question: how is right-slip in the Salton Trough passed through or around the San Bernardino Mountains? We address this question below.

The San Andreas fault system in the vicinity of the central Transverse Ranges: a product of left and right steps in a right-lateral fault zone

The neotectonic setting of the San Gorgonio Pass region owes its origin and kinematics to a bottleneck that gradually evolved in the San Andreas fault during the Pleistocene as the San Bernardino Mountains block was projected across the path of the San Andreas fault and multiple right-lateral strands successively were deformed and abandoned. The geometric effect of these events is apparent from a geologic map of the region: the northwest-oriented trace of the Coachella Valley segment of the San Andreas fault is offset or stepped left about 15 km from the northwest-oriented trace of the Mojave Desert segment (fig. 5). The modern neotectonic framework thus has inherited a bottleneck that must be accommodated in the late Quaternary strain budget of the region.

Any neotectonic model that attempts to distribute strain through or around the San Gorgonio Pass bottleneck must accommodate the following elements: (1) right slip on the Coachella Valley segment of the San Andreas fault falls off as the segment approaches the Transverse Ranges segment; (2) convergence is occurring in San Gorgonio Pass; (3) the San Bernardino valley region is undergoing extension; and (4) right slip on the Mojave Desert segment carries southeastward toward the San Bernardino Mountains segment by way of the San Bernardino strand, but does not carry simply or easily through that segment. To accommodate these elements we propose a speculative model (fig. 6) in which slip is carried around, not through, the Transverse Ranges segment of the San Andreas fault by a complicated series of left and right steps that have created compressional and extensional fault complexes in San Gorgonio Pass and the San Bernardino valley region.

We start with the premise that right-slip occurs on the San Andreas fault in the Coachella Valley but does not carry through the San Bernardino Mountains. We assume that about 25 mm of annual slip occurs on the Coachella Valley segment of the San Andreas between the Salton Sea and the northern Coachella Valley; this figure is consistent with a range of slip values indicated by geologic and geodetic data (Keller and others, 1982; Savage and others, 1979; Savage, 1983). Modern neotectonic slip accounts for the youthful tectonic geomorphology displayed by the San Andreas fault along this segment (Keller and others, 1982; Clark, 1984). However, northwest of Desert Hot Springs, the Coachella Valley segment loses its fresh tectonic geomorphology and our preliminary data suggest that late Quaternary alluvial units have not been displaced significantly by the fault. Farther northwest, the Wilson Creek, Mission Creek, and Mill Creek strands of the San Bernardino Mountains segment are paleotectonic faults that have been abandoned as throughgoing right-lateral strands of the San Andreas fault. Thus, we conclude that during late Quaternary time, most if not all right slip on the San Andreas fault in the northern Coachella Valley has stepped left onto the Banning fault. This process may account for two features. (1) As slip has been transferred across the gap between the two faults, the youthful Indio Hills have been squeezed into an anticlinal uplift. Thus, some percentage of right-slip on the San Andreas would be converted into compressional strain. (2) A left step between the San Andreas and Banning faults in the northern Coachella Valley may explain the absence of fresh tectonic geomorphology for the Banning fault near its junction with the San Andreas fault in the southern Indio Hills (Keller and others, 1982): youthful slip along this segment of the Banning fault would not be necessary if right slip were transferred to the strand farther to the northwest.

Between the Indio Hills and San Gorgonio Pass, late Quaternary right-slip on the Banning fault is indicated by youthful tectonic geomorphology and by right-lateral displacement of late Pleistocene fluvial gravels 2 or 3 km into the Pass (Sheet 2, F-F', G-G'). Moreover, Allen and Sieh (1983) report 2 mm of annual creep on the fault just east of San Gorgonio Pass. The Holocene history of the Banning fault in the Coachella Valley has not been documented, however, and modern right-slip may step still farther west (left) from the Banning fault onto the Garnet Hill fault. This speculation is based on two features: (1) Several youthful domelike uplifts of Quaternary gravel that occur between the two faults in the vicinity of Whitewater River and Garnet Hill (Allen, 1957, fig. 1 of pl. 6; Dibblee, 1982, p. 166, oblique aerial photograph) may reflect compression within a left-stepping zone; and (2) geomorphic evidence suggests that late Quaternary fluvial gravels in the east part of San Gorgonio Pass may have been displaced right-laterally by the Garnet Hill fault. Whether or not latest right-slip has occurred on the Banning fault or the Garnet Hill fault, neither strand can be traced beyond the eastern San Gorgonio Pass area, and late Quaternary right-slip in the Coachella Valley must have been partly absorbed within the San Gorgonio Pass fault complex.

Although right-slip on the San Andreas fault largely may have been absorbed by convergence within San Gorgonio Pass, some component of slip may step left through San Gorgonio Pass and onto the San Jacinto fault, where it would be added to the 10 mm/year average slip determined by Sharp (1981) for the fault in the Anza area (fig. 6). Local acceleration of slip on the San Jacinto might explain four features of the region. (1) Northwest-trending faults of the Beaumont Plain that appear to have normal dip-slip displacements may reflect extensional fragmentation created as slip steps left to the San Jacinto fault. (2) The San Jacinto Valley is a graben that is rapidly subsiding (Morton, 1977) between right- and left-stepping strands of the San Jacinto fault (Cheatum and Combs, 1973, figs. 2, 4). Rapid subsidence may reflect addition of right-slip acquired from the San Andreas fault. (3) The San Jacinto Valley has been the site of two earthquakes of magnitude (M_L) greater than 6.5 during the last 85 years (Thatcher and others, 1975; Sanders and Kanamori, 1984), and the southern San Jacinto Valley has high rates of microseismicity (Brune and Allen, 1967; Cheatum and Combs, 1973); this may reflect an increased potential for seismic activity in response to locally accelerated slip in the San Jacinto Valley area. (4) The San Jacinto fault in the San Jacinto Valley is accumulating about 25 mm/year of right-lateral shear strain (Savage and Prescott, 1967); this departure from the long-term slip rate determined by Sharp (1981) may reflect local acceleration of strain accumulation due to slip acquired from the San Andreas fault.

The neotectonic framework of the San Bernardino valley region includes several distinctive features whose origin and kinematics may require transfer of slip from the San Jacinto fault back to the San Andreas (fig. 6). (1) The San Bernardino strand of the San Andreas fault appears to die out southeastward toward San Gorgonio Pass; (2) the greater San Bernardino valley region is the site of dip-slip fault complexes like the Crafton Hills horst-and-graben complex and the Peters and Tokay Hill faults, which appear to represent an extensional strain field; (3) south of the San Bernardino valley, the San Jacinto fault has a pronounced convex-west bend which may form an impediment to right-slip; (4) the San Jacinto fault between Reche Canyon and Cajon Pass may represent a seismic-slip gap (Thatcher and others, 1975); (5) Morton and Matti (1987) have shown that the San Jacinto fault in the southeastern San Gabriel Mountains does not rupture latest Quaternary alluvium; the youngest branch of the San Jacinto system in this vicinity appears to be the Glen Helen fault, and even this strand is concealed by youngest alluvial deposits in the Cajon Pass region; and (6) the San Bernardino valley region is traversed by northeast-trending left-lateral seismicity lineaments (Green, 1983; Nicholson and others, 1986) that may define the boundaries of clockwise-rotating blocks (Nicholson and others, 1986). In combination, these features may require a common explanation.

We propose that slip on the San Jacinto fault gradually steps right onto the modern San Andreas fault throughout the San Bernardino valley region (fig. 6). By this interpretation, the San Bernardino valley has moved northwestward away from the San Gorgonio Pass region, and the crust between the two regions is pulling apart. This extension is manifested by faults like those in the Crafton Hills extensional complex. Northwestward movement of the San Bernardino valley has occurred along the San Bernardino strand, which extends as a youthful neotectonic feature southeastward from Cajon Pass to the Crafton Hills-Oak Glen region but may not necessarily continue through San Gorgonio Pass and on into the Coachella Valley to the Banning fault. In the Devore area southeast of Cajon Pass, slip may step right from the San Jacinto fault to the Glen Helen fault, which has scarps and sag ponds in the Devore area, and thence to the San Bernardino strand--thereby creating an extensional strain field that gives rise to normal dip-slip displacements on the Peters and Tokay Hill faults. A right step from the San Jacinto to the Glen Helen may explain a distinctive seismicity lineament between the inferred traces of the two faults beneath the floodplains of Cajon and Lytle Creeks (Green, 1983, fig. 7). Extension created by a regional right step from the San Jacinto to the San Andreas fault may occur throughout the San Bernardino Valley region, and may create high heat flow that accounts for hot springs and subsurface hot-water zones that occur at several locations in the valley region.

Right-stepping transfer of slip and (or) accumulated strain from the San Jacinto to the San Andreas would create a right-lateral shear couple that could generate clockwise block rotations of the type proposed by Nicholson and others (1986). During the period between large earthquakes on either the San Jacinto or San Andreas faults (the interseismic period of Nicholson and others, 1986), accumulated shear strain within the San Bernardino valley region partly could be released by block rotations and extensional faulting; large earthquake events on the San Andreas and San Jacinto faults would release strain accumulated along the margins of the shear couple. Thus, two styles of seismicity might alternate through time.

We have not documented geometric and kinematic relations between the San Jacinto, San Andreas, and Cucamonga faults in the vicinity of Cajon Pass and the southeastern San Gabriel Mountains. However, one point is clear: at the surface, right-slip on the San Jacinto fault does not pass easily into the San Andreas fault. For example, northwestward migration of the Perris block by right-lateral displacements on the San Jacinto fault partly has been taken up by late Pleistocene and Holocene thrust-fault displacements within the Cucamonga fault zone (Morton and others, 1982; Matti and others, 1982; Morton and Matti, 1987; J. C. Matti, D. M. Morton, J. C. Tinsley, and L. D. McFadden, unpubl. data). Thus, the fault zone represents a zone of convergence between the Peninsular and Transverse Ranges Provinces: to the south, the Perris block and Peninsular Ranges are slipping northwestward along traces of the San Jacinto fault zone; however, this right-lateral migration apparently is impeded by the eastern Transverse Ranges, and the Perris block and alluviated lowlands of the upper Santa Ana River Valley apparently are being thrust beneath the eastern San Gabriel Mountains.

Convergence rates across the Cucamonga fault must be factored into the overall strain budget of the region. Here, the neotectonic San Andreas and San Jacinto faults have late Quaternary slip rates of 25 mm/year and 8 to 12 mm/year, respectively (Weldon and Sieh, 1985; Sharp, 1981). Our studies suggest a minimum convergence rate of 5 mm/year for the Cucamonga fault zone during latest Pleistocene and Holocene time--a rate that could double to 10 mm/year if the faulted alluvial succession proves to be younger than we believe. Thus, if the Cucamonga fault zone represents convergence between the Peninsular and Transverse Ranges Provinces, then half to nearly all of the 8 to 12 mm of annual slip on the San Jacinto fault could have been taken up by latest Pleistocene and Holocene convergence within the Cucamonga fault zone. Such a model would imply that part or all of the slip on the San Jacinto fault has not contributed to slip on the San Andreas during latest Quaternary time. Viewed in this way, the Cucamonga fault may represent a major zone of convergence between large crustal blocks.

By contrast, Weldon (1984, 1985a,b) suggests that, even though the San Jacinto fault zone may not have a surface connection with the San Andreas fault (Morton, 1975b), the 8 to 12 mm of annual slip on the San Jacinto nevertheless feeds into the San Andreas and contributes to slip on that fault. If this interpretation is correct, then the annual 5-mm convergence rate within the Cucamonga fault zone may not reflect wholescale convergence between major crustal blocks of the Peninsular and Transverse Ranges but instead may simply reflect interactions between local small blocks in a region where the San Jacinto and San Andreas faults merge in a complicated manner. This interpretation might also account for the geographically segmented strain-release behavior that appears to have characterized the Cucamonga fault zone during latest Pleistocene and Holocene time (Morton and Matti, in press).

CONCLUSIONS

The vicinity of the south-central Transverse Ranges is traversed by multiple faults of the San Andreas transform system--including the Banning, San Andreas, and San Jacinto faults. After generating 15 to 25 km of right-slip during late Miocene time, the Banning fault was abandoned in early Pliocene time and was succeeded by the San Andreas fault. At the latitude of the Pinto Mountain fault, crustal convergence created a structural knot that led to the evolution of multiple fault strands; these constitute the San Bernardino Mountains segment of the San Andreas. The structural knot evolved gradually during the late Pliocene and Pleistocene, and created a left step in the San Andreas fault as convergence coupled with left-lateral displacements on the Pinto Mountain fault gradually projected the San Bernardino Mountains block across the path of the San Andreas; the multiple right-lateral strands developed sequentially as the fault attempted to maintain a geometrically simple trace through the left-stepping region. The Wilson Creek and Mission Creek faults are the oldest strands, and sequentially generated about 130 km of displacement before the Mission Creek fault was abandoned in the Pleistocene (prior to 0.5 m.y. ago). In late Pleistocene time the Mill Creek fault evolved inboard of the locked-up Mission Creek fault and generated 8 km of displacement before it was abandoned as a throughgoing strand.

The Coachella Valley and Mojave Desert segments of the San Andreas fault are offset about 15 km by the left step in the Transverse Ranges segment. The modern San Andreas fault apparently is responding to this left step by transferring slip from the Coachella Valley segment to the Banning fault and thence into San Gorgonio Pass, where right-slip has been absorbed within the San Gorgonio Pass fault complex. Some component of slip may step farther west to the San Jacinto fault in the San Jacinto Valley. Throughout the San Bernardino valley region, slip steps from the San Jacinto fault back onto the San Bernardino strand of the San Andreas, which creates a regional right-lateral shear couple between the two strike-slip faults and accounts for extensional fault complexes like the Crafton Hills horst-and-graben complex and the Peters and Tokay Hill faults. Thus, the modern neotectonic framework of the south-central Transverse Ranges reflects an integrated regional response to an evolving left step in the San Andreas fault.

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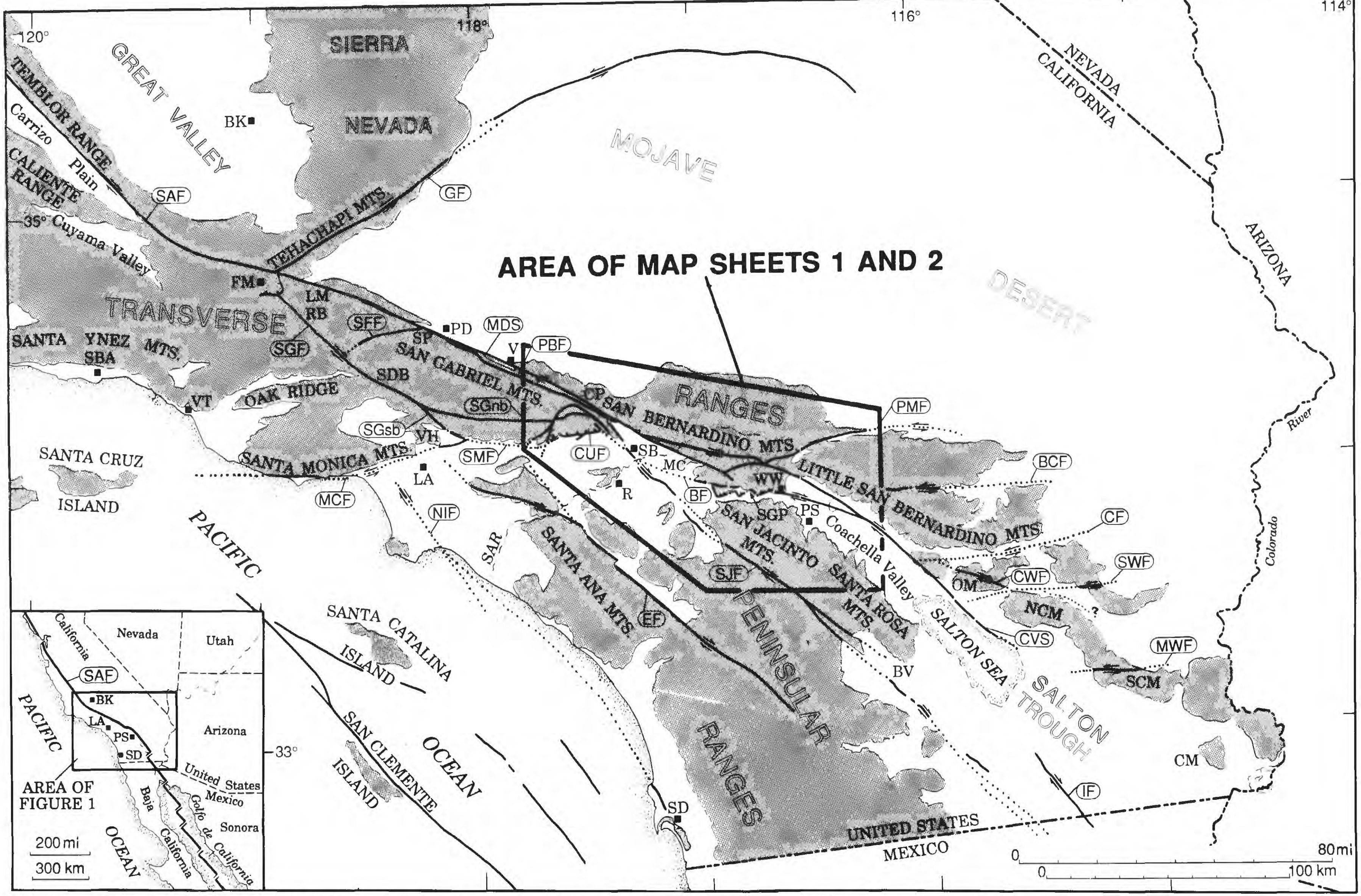

Figure 1.--Index map showing geographic features and faults discussed in this report. BCF, Blue Cut fault; BF, Banning fault; BK, Bakersfield; BV, Borrego Valley region; CF, Chiriaco fault; CM, Cargo Muchacho Mountains; CP, Cajon Pass region; CUF, Cucamonga fault; CVS, Coachella Valley segment, San Andreas fault; CWF, Clemens Well fault; EF, Elsinore fault; FM, Frazier Mountain region; GF, Garlock fault; IF, Imperial fault; LA, Los Angeles; LM, Liebre Mountain; MCF, Malibu Coast-Santa Monica-Raymond fault; MC, Mill Creek; MDS, Mojave Desert segment, San Andreas fault; MWF, Mammoth Wash fault; NCM, northern Chocolate Mountains; NIF, Newport-Inglewood fault; OM, Orocopia Mountains; PBF, Punchbowl fault; PD, Palmdale; PMF, Pinto Mountain fault; R, Riverside; RB, Ridge Basin; SAF, San Andreas fault; SAR, Santa Ana River; SB, San Bernardino; SBA, Santa Barbara; SBM, San Bernardino Mountains; SCM, southern Chocolate Mountains; SD, San Diego; SDB, Soledad Basin; SFF, San Francisquito fault; SGF, San Gabriel fault; SGnb, north branch, San Gabriel fault; SGsb, south branch, San Gabriel fault; SGP, San Gorgonio Pass; SJF, San Jacinto fault; SMF, Sierra Madre fault; SP, Sierra Pelona; SWF, Salton Wash fault; V, Valyermo; VT, Ventura; WW, Whitewater.

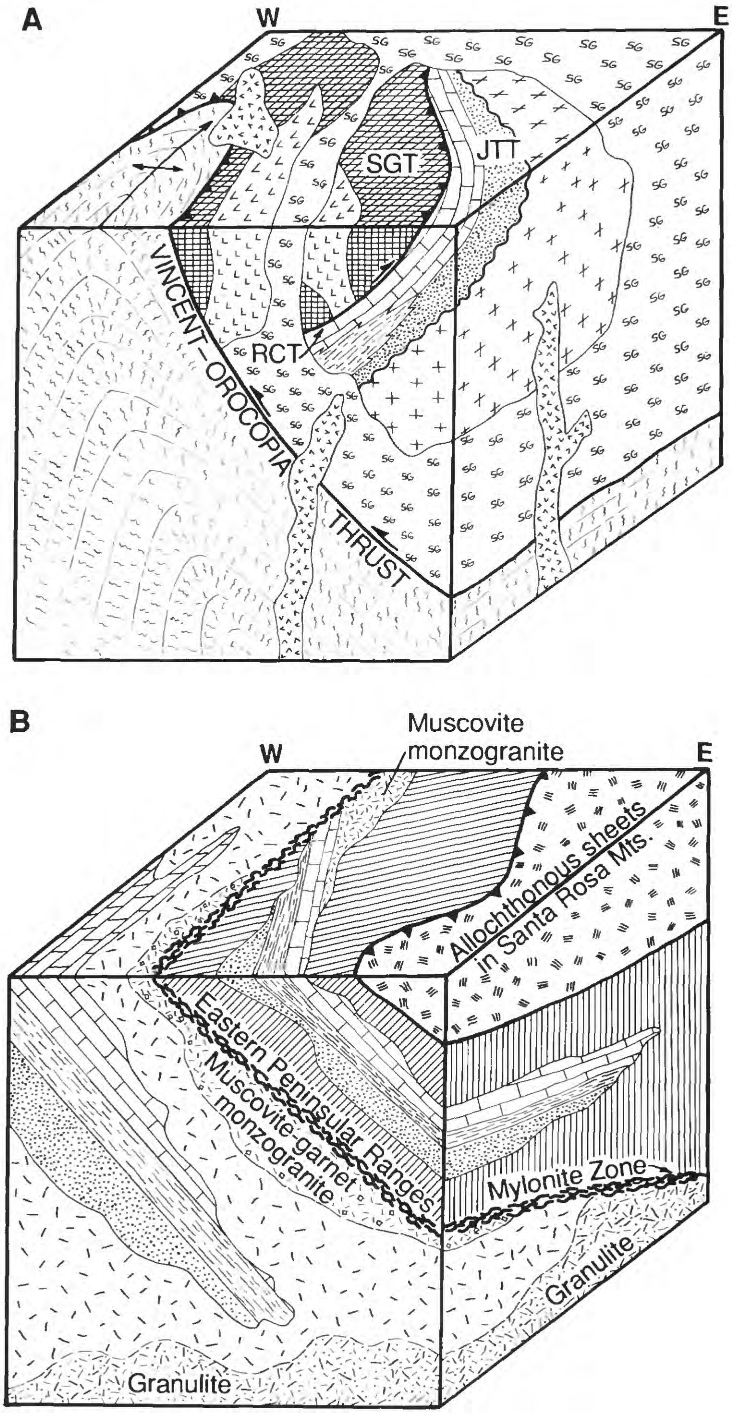

Figure 2.--Block diagrams schematically illustrating relations among major lithologies and structures in rocks of San Gabriel Mountains-type, Peninsular Ranges-type, and San Bernardino Mountains-type. W, west; E, east. (A) Rocks of San Gabriel Mountains-type, including rocks of Powell's (1982a,b) Joshua Tree terrane (JTT) and San Gabriel terrane (SGT) separated by the pre-Cretaceous Red Cloud thrust (RCT). The Joshua Tree terrane includes Proterozoic metaquartzite, pelitic schist and gneiss, and marble resting nonconformably on granitic gneiss; the San Gabriel terrane includes anorthosite and gabbro, syenite-mangerite, and orthogneiss (augen gneiss and retrograded granulite). (B) Rocks of Peninsular Ranges-type, including lower and upper plates of the Eastern Peninsular Ranges mylonite zone of Sharp (1979). In both plates, metasedimentary rocks include metaquartzite, pelitic gneiss and schist, graphitic schist, and marble.

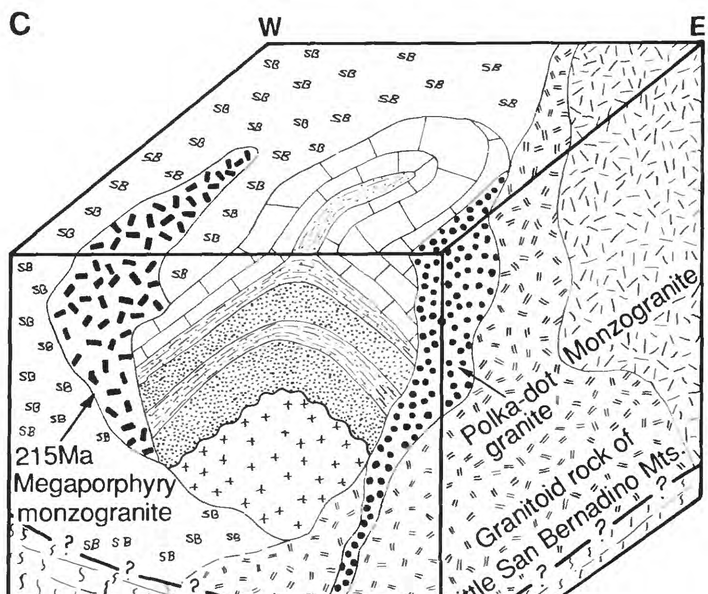

Figure 2 (Continued).--(C) Rocks of San Bernardino Mountains-type. Metasedimentary rocks include metaquartzite, pelitic gneiss and schist, and marble that are comparable to uppermost Proterozoic and Paleozoic rocks of the Cordilleran miogeocline (Stewart and Poole, 1975). SB indicates undifferentiated metasedimentary rocks of San Bernardino Mountains-type.

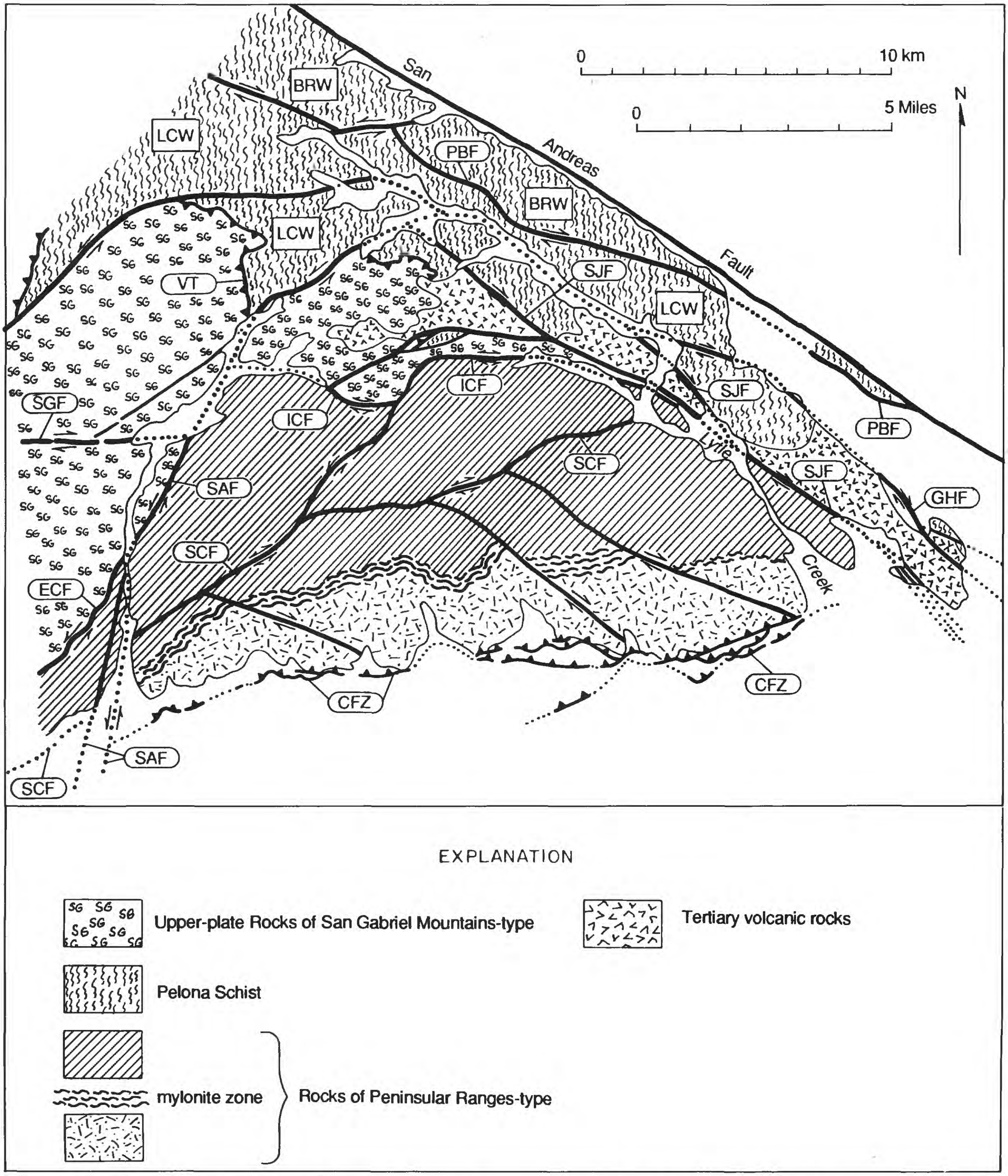

Figure 3.--Distribution, geologic relations, and nomenclature of geologic terranes and Neogene faults in the southeastern San Gabriel Mountains (modified from Morton, 1975a, figs. 1,2). BRW, Blue Ridge Window of Pelona Schist; CFZ, Cucamonga fault zone; ECF, Evey Canyon fault; GHF, Glen Helen fault; ICF, Icehouse Canyon fault; LCW, Lytle Creek window of Pelona Schist; PBF, Punchbowl fault; SAF, San Antonio fault; SCF, Stoddard Canyon fault (includes San Gabriel fault [south branch] west of the San Antonio fault); SGF, San Gabriel fault (north branch); SJF, faults traditionally referred to the San Jacinto fault; VT, Vincent thrust.

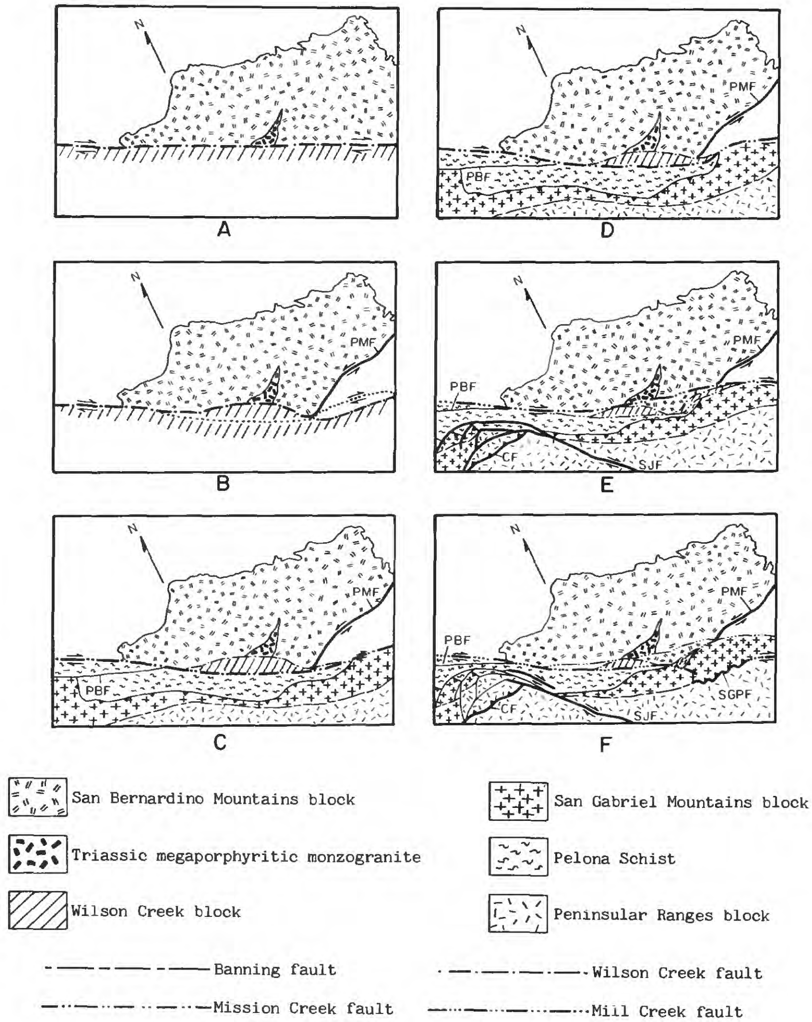

Figure 4.--Schematic diagram summarizing the history of the San Andreas fault system in the vicinity of the central Transverse Ranges. Heavy lines indicate active faults; lighter lines indicate inactive faults. CF, Cucamonga fault; PBF, Punchbowl fault. (A) Approximately 40 km of right slip on the Wilson Creek-Punchbowl strand of the San Andreas fault juxtaposes the Wilson Creek block against the San Bernardino Mountains block. The total geographic extent of the Wilson Creek block and its relations with other terranes to the northwest, west, and southeast are not indicated because they are not known. (B) The Wilson Creek-Punchbowl strand is compressed into a trace that is sinuous regionally, and the strand locks up. Dotted line shows the future trace of the Mission Creek strand of the San Andreas. (C) The Mission Creek strand evolves outboard (west) of the Wilson Creek-Punchbowl strand adjacent to the southeastern San Bernardino Mountains but inboard (east) of the strand to the southeast. This allows the Punchbowl fault to be conveyed northwestward away from its dismembered counterpart--the Wilson Creek fault--that remains stranded against the San Bernardino Mountains. The Mission Creek strand eventually generates about 89 km of right slip that juxtaposes the San Gabriel Mountains block against the Wilson Creek and San Bernardino Mountains blocks. (D) The Mission Creek strand gradually is deformed as the San Bernardino Mountains block is projected across the path of the San Andreas fault by left-slip on the Pinto Mountain fault (PMF). These events create a left step between the Coachella Valley and Mojave Desert segments of the San Andreas fault (see fig. 5). (E) The San Jacinto fault evolves outboard (west) of the locked-up Mission Creek strand, probably about 1.0 to 1.5 m.y. ago; the Mill Creek strand of the San Andreas evolves inboard of the locked-up Mission Creek strand at a later time--perhaps 0.5 m.y. ago . (F) The Mill Creek strand is locked up by continued left slip on the Pinto Mountin fault, leading to the modern neotectonic setting (fig. 6) where slips steps left from the Coachella Valley segment of the San Andreas fault to the Banning fault and thence into the San Gorgonio Pass fault zone (SGPF), where the Peninsular Ranges block is converging with the San Gabriel Mountains block.

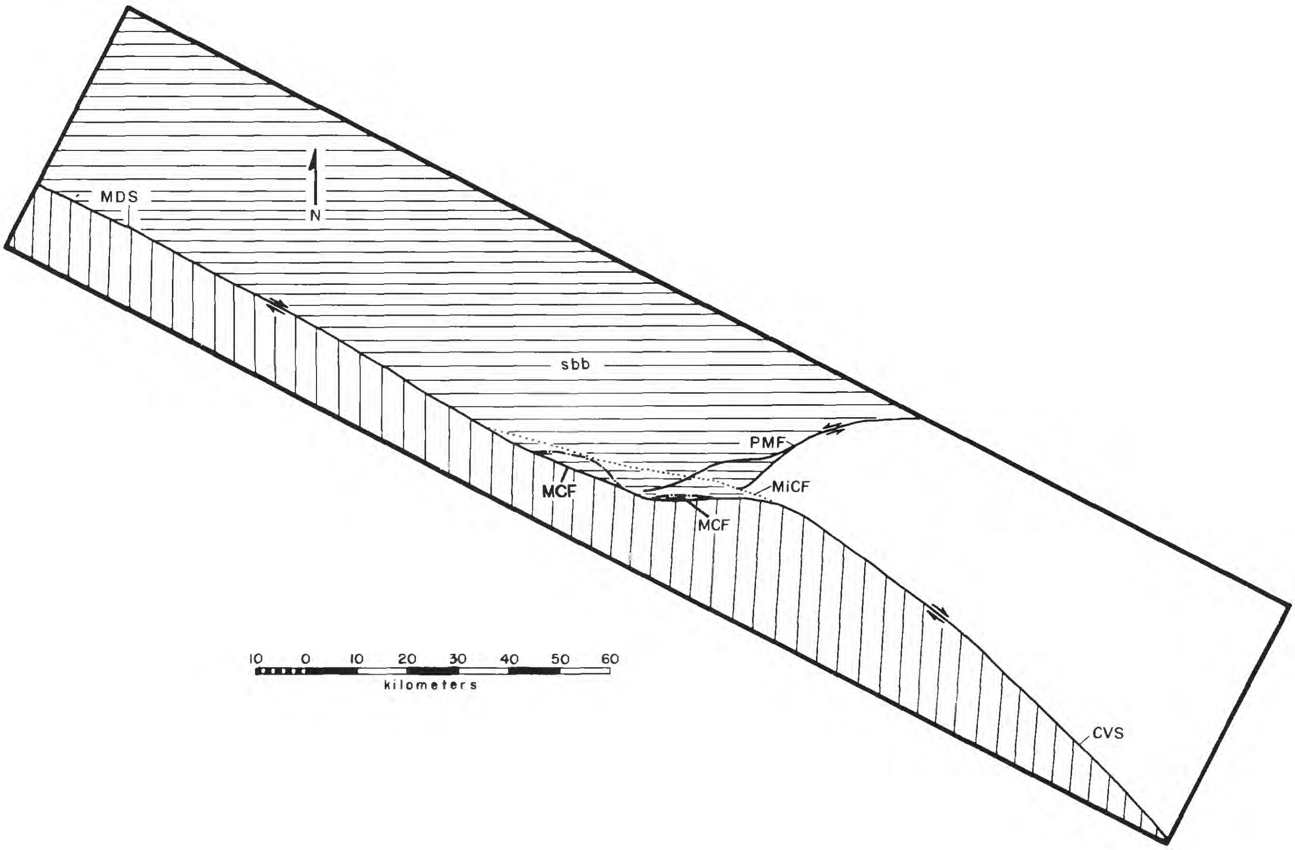

Figure 5.--Diagram illustrating the left step that displaces the Coachella Valley and Mojave Desert segments of the San Andreas fault in the vicinity of San Gorgonio Pass. The diagram represents geologic relations in the Pleistocene, about 750,000 yr ago. The Mission Creek strand of the San Andreas (MCF) has generated all of its right slip, has been abandoned by the San Andreas system, and eventually will be succeeded by the Mill Creek strand (MiCF) that will evolve along the dotted trace and will generate about 8 km of right slip. The San Bernardino Mountains block (sbb) has been projected across the path of the San Andreas fault, accompanied by left-slip on the Pinto Mountain fault (PMF). These events have displaced the Mojave Desert segment (MDS) and Coachella Valley segment (CVS) by about 15 km--the amount of left slip on the Pinto Mountain fault as determined by Dibblee (1968b). Exotic rocks of the Wilson Creek block, originally juxtaposed against the San Bernardino Mountains block by right-slip on the Wilson Creek strand (WCF) of the San Andreas, became attached to the San Bernardino Mountains block once they were bypassed by the Mission Creek strand; since that time, the Wilson Creek and San Bernardino Mountains blocks have behaved as a single unit that has been projected across the path of the San Andreas fault.

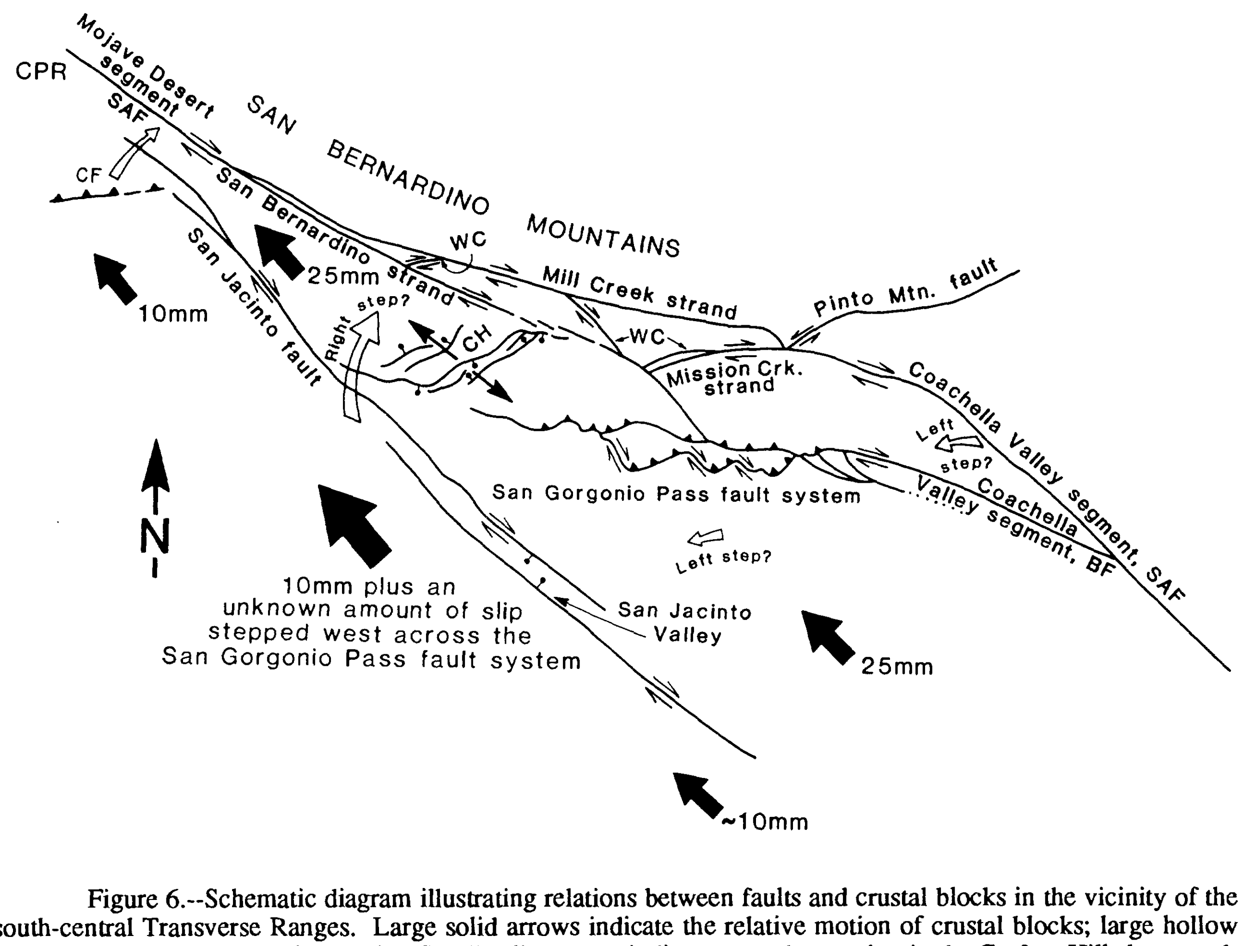

Figure 6.--Schematic diagram illustrating relations between faults and crustal blocks in the vicinity of the south-central Transverse Ranges. Large solid arrows indicate the relative motion of crustal blocks; large hollow arrows indicate lateral transfer of slip. Small solid arrows indicate crustal extension in the Crafton Hills horst-and-graben complex. BF, Banning fault; CF, Cucamonga fault; CH, Crafton Hills; CPR, Cajon Pass region; SAF, San Sandreas fault; WC, Wilson Creek strand, San Andreas fault. Ten millimeters of annual slip on the San Jacinto fault is assumed from data of Sharp (1981).

TABLE 1. NOMENCLATURAL USAGE FOR FAULTS OF THE SAN ANDREAS FAULT SYSTEM

Usage in this Chapter	Previous Usage
	San Andreas Fault Zone
Salton Trough	
Coachella Valley segment, San Andreas fault	North Branch, San Andreas fault (Dibblee, 1954, 1967b, 1975a; Dillon, 1975; Peterson, 1975) Mission Creek fault (Allen, 1957; Farley,1979)
Coachella Valley segment, Banning fault	South Branch, San Andreas fault (Dibblee, 1954, 1968a, 1975a; Dillon, 1975) Banning fault (Allen, 1957)
San Bernardino Mountains	
Wilson Creek strand, San Andreas fault	Wilson Creek fault (Dibblee, 1964, 1982b; Gibson, 1964, 1971; Sadler and Demirer, 1986)
Mission Creek strand, San Andreas fault	Mission Creek fault (Allen, 1957; Ehlig, 1977; Farley, 1979; Matti and others, 1983a, 1985)
Mill Creek strand, San Andreas fault	Mill Creek fault (Allen, 1957; Gibson, 1964, 1971; Ehlig, 1977; Farley, 1979); north branch, San Andreas fault (Dibblee, 1964, 1967b, 1968a, 1975a, 1982b)
San Bernardino strand, San Andreas fault	South Branch, San Andreas fault (Dibblee, 1964, 1968a, 1975a, 1982b)
San Gabriel Mountains–Mojave Desert	
Punchbowl fault	Noble (1953; 1954a, b); Dibblee (1967a, 1968a, 1982a); Ehlig (1975, 1981); Barrows and others (1985, 1987); Barrows (1975, 1987)
Nadeau fault (south branch)	Barrows and others (1985, 1987); Barrows (1987)
Nadeau fault (north branch)	Barrows and others (1985, 1987); Barrows (1987)
Mojave Desert strand	Dibblee (1967a, 1968a, 1982a); "main trace" of Barrows and others (1985, 1987); Barrows (1975, 1987)
Little Rock fault	Barrows and others (1985, 1987); Barrows (1975, 1987)
	San Gabriel Fault Zone
Salton Trough through San Bernardino Valley	
Banning fault	Matti and Morton (1982); Matti and others (1985)
San Gabriel Mountains	
San Gabriel fault (south branch)	No consistent or documented usage
Stoddard Canyon fault	Interpreted as a left-lateral fault by Morton (1975a)
San Gabriel fault (north branch)	Ehlig (1973, 1975, 1981, 1982); Dibblee (1968a, 1982a); Crowell (1975a, c; 1981, 1982a)
Icehouse Canyon fault	Evans (1982); Matti and others (1985); May and Walker (1989)
Cajon Pass	
Cajon Valley fault	Dibblee (1967a, 1968a); Woodburne and Golz (1972); Matti and others (1985); Weldon (1986); Meisling and Weldon (1989)
	San Jacinto Fault Zone
San Jacinto Mountains to San Bernardino Valley	
San Jacinto fault	Sharp (1967); Matti and others (1985)
San Gabriel Mountains	
San Jacinto fault	Morton (1975a); Dibblee (1968a, 1975a, 1982a)
Glen Helen fault	Morton (1975a); Matti and others (1985); Morton and Matti (1987, this volume)
	Clemens Well–Fenner–San Francisquito Fault Zone
Orocopia Mountains	
Clemens Well fault	Crowell (1975b); Powell (1981, 1986, this volume)
San Gabriel Mountains	
Fenner fault	Dibblee (1967a, 1968a, 1982a); Powell (1981, 1986, this volume); Ehlig (1975, 1981); Barrows and others (1985, 1987); Barrows (1975, 1987)
Soledad Basin region	
San Francisquito fault	Dibblee (1967a, 1968a, 1982a); Powell (1981,1986, this volume); Ehlig (1975, 1981); Barrows and others (1985, 1987); Barrows (1975, 1987)

From Matti and Morton, 1992

TABLE 2. DOCUMENTATION FOR K/Ar RADIOMETRIC AGE DATES FROM BASALT IN THE PAINTED HILL FORMATION, WHITEWATER AREA*

Sample	K_2O (%)	^{40}Ar (moles/gm)	$^{40}Ar/\Sigma^{40}Ar$ (%)	Age (Ma)
DG-1A	1.133, 1.121	9.813×10^{-12}	60	6.04 ± 0.18
DG-1B	1.095, 1.087	9.341×10^{-12}	66	5.94 ± 0.18

Constants used in age calculation: $\lambda B = 4.963 \times 10^{-10}\ yr^{-1}$
$\lambda_{\varepsilon} + \lambda_{\varepsilon'} = 0.581 \times 10^{-10}\ yr^{-1}$
$^{40}K/K_{total} = 1.167 \times 10^{-4}$ mole/mole

*A basalt flow in the lower part of the Painted Hill Formation north of the Banning fault has yielded two concordant whole-rock K/Ar age determinations of 6.04 ± 0.18 and 5.94 ±0.18 Ma. The analyses were performed by J. L. Morton at the U.S. Geological Survey. Both samples are fresh, fine-grained basalt with plagioclase phenocrysts as long as 0.5 cm. The whole-rock samples were crushed and sieved, then treated with hydrofluoric and nitric acid to reduce atmospheric argon contamination. Potassium was analyzed by flame photometry; argon was analyzed by standard isotope-dilution procedures, using a 60°, 15.2-cm radius, Neir-type mass spectrometer. The overall analytical uncertainty of the ages is approximately 3 percent and is a combined estimate of the precision of the argon and potassium measurements at 1 standard deviation.

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