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Distribution and geologic relations of fault systems in the vicinity of the Central Transverse Ranges, southern California

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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 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 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 Transverse Ranges, Mojave Desert, and Coachella Valley segments. The complex Transverse Ranges 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 Transverse Ranges 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 generated about 150 km of right-lateral displacement during Pliocene and Pleistocene time, but we presently cannot apportion this displacement between the two strands. The Wilson Creek fault, the older strand, generated part of the 150-km displacement before it was deformed into a curving trace in the vicinity of the San Bernardino Mountains; it was succeeded by the Mission Creek fault, which generated the balance of the 150-km displacement before it was deformed and abandoned in late Pleistocene time. The Mill Creek fault 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 fault 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 distribution and geologic setting 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 compressional 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[1] 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

[1]We use paleotectonic and neotectonic to refer to the relative recency of tectonic movements. Some faults discussed in this report were active as recently as 1 m.y. ago but no longer are important in the modern faulting framework; other faults have evolved more recently and play primary modern roles. In tectonically stable regions, fault activity within so short a period as the last 5 m.y. probably would be viewed entirely as "neotectonic"; however, in an active region like southern California, where multiple fault complexes have evolved and experienced episodic activity during the last 5 m.y. or so, it is useful to distinguish relatively modern neotectonic faults from paleotectonic faults that generated earlier activity but which now are not primary components of the modern tectonic framework. The cutoff between neotectonic and paleotectonic activity is not rigorous. We find it useful to restrict neotectonic to the last 100,000 years or so and we use the term "modern neotectonic" to emphasize youthful activity within this period.

system. Our purpose is fourfold: (1) to describe various strands of the San Andreas transform system in the vicinity of the central Transverse Ranges and to summarize the geology of crystalline and sedimentary rocks that are bounded by these strands; (2) to outline the history of the San Andreas and Banning faults; (3) to identify fault zones that are not part of the San Andreas transform system but which have interacted with it; and (4) to present a model that relates modern faults of the central Transverse Ranges within a coherent regional framework.

This report is based largely on geological studies conducted during the last several years under the auspices of two U.S. Geological Survey programs--the National Earthquake Hazards Reduction Program and the Wilderness Mineral-Resource Evaluation Program. The results of some of these studies have been published (Morton and Miller, 1975; Matti and Morton, 1975, 1982; Morton, 1975a, 1978a,b,c; Morton and others, 1980; Matti and others, 1982a,b,c; Matti and others, 1983; Cox and others, 1983; Morton and Matti, in press, a,b,c; Matti and others, in press). However, much of the geologic mapping undertaken in conjunction with these studies has not yet been published. This report and the accompanying map represent a preliminary summary of these unpublished studies.

MAJOR STRUCTURAL BLOCKS[2]

Three major tectonic or structural blocks dominate the tectonic framework of the central Transverse Ranges and vicinity--the Peninsular Ranges, San Gabriel Mountains, and San Bernardino Mountains blocks (fig. 1). The Peninsular Ranges block (Jahns, 1954) consists of Cretaceous granitoid rocks (tonalite, quartz diorite, granodiorite) that have intruded prebatholithic metasedimentary rocks (pelitic schist and gneiss, metaquartzite, marble, quartzofeldspathic gneiss and schist). Geophysical and seismological studies suggest that the block forms a thick crustal mass that is rigid and strong. The San Gabriel Mountains block consists of two crustal layers separated by a low-angle tectonic contact--the Vincent thrust. The upper thrust plate consists of deformed Mesozoic plutons of various compositions and ages that have intruded prebatholithic crystalline rocks. The prebatholithic rocks largely are Precambrian in age, and are related to the gneisses and anorthosite-syenite complex 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--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). The Pelona Schist crops out in large windows in the eastern San Gabriel Mountains, and occurs in a large window that mostly has been buried beneath Quaternary sediment of the San Bernardino valley. Both lower and upper plates are intruded by high-level Miocene dikes and granitoid plutons that were emplaced after initial juxtaposition of the two plates (Miller and Morton, 1977). The San Bernardino Mountains block consists of Mesozoic granitoid rocks of various compositions and ages that have intruded prebatholithic metasedimentary rocks (late Precambrian and Paleozoic metaquartzite, marble, pelitic schist and gneiss) and orthogneiss (Precambrian); these rocks are similar to those in the Mojave Desert. Along its southwestern margin, the San Bernardino Mountains block includes the Wilson Creek block--a small exotic slice of crystalline rocks and Tertiary sedimentary rocks that was juxtaposed against the San Bernardino Mountains block in early Pliocene time by right-lateral displacements on the San Andreas fault; the two blocks have behaved as a single unit for the last few million years. Like the San Gabriel Mountains block, the San Bernardino Mountains block may be a layered terrane with batholithic and prebatholithic rocks at the surface separated from Pelona Schist in the subsurface by a low-angle fault comparable to the Vincent thrust.

RIGHT-LATERAL STRIKE-SLIP FAULTS

Three major right-lateral faults traverse the vicinity of the central Transverse Ranges--the Banning, San Jacinto, and San Andreas faults. We follow other workers who view these faults as members of 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, presumably 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). The San Andreas and San Jacinto faults are youthful elements of the transform system; the Banning fault is an older element that has been abandoned by the system.

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 had identified. Although Hill (1928, plate II) did not specifically designate the Banning fault on his map, he evidently was applying 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 geographic segments.

[2]As used here, structural blocks are domains that have behaved as coherent structural units during the late Miocene through Quaternary history of the central Transverse Ranges and vicinity. These blocks should not be viewed as distinct lithologic or tectonostratigraphic terranes: in fact, some lithologies may occur in two or even all three blocks. For example, prebatholithic metasedimentary rocks of the Peninsular Ranges and San Bernardino Mountains blocks may prove to be parts of a single lithostratigraphic terrane, even though they occur in discrete structural blocks relative to the late Cenozoic history of southern California.

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 paleotectonic ancestral strand can only be inferred on the basis of gravity data (Willingham, 1971, 1981) and indirect geologic evidence.

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 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).

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

The Banning fault is an ancient strike-slip fault zone that locally has been reactivated by Quaternary tectonism. The ancestral zone appears to have undergone two distinct phases of faulting: (1) an episode of left-lateral faulting prior to late Miocene time, and (2) an episode of right-lateral faulting during latest Miocene and earliest Pliocene time. Although these separate displacements may have occurred along multiple traces within a narrow fault zone, it is more likely that the younger right-lateral activity reactivated the older left-lateral trace and reversed the sense of displacement.

Left-lateral history.--Left-lateral displacements on the Banning fault can be inferred from relations in the San Gorgonio Pass area, where the fault intervenes between two distinctly different suites of crystalline rock--Cretaceous batholithic granitoid rocks and prebatholithic metasedimentary rocks of the Peninsular Ranges block to the south, and Mesozoic and Precambrian granitoid rocks and gneissic granitoid rocks of the San Gabriel Mountains block to the north. The Banning fault cannot actually be observed to juxtapose the two crystalline suites because Quaternary and Tertiary sedimentary deposits intervene between them and cover the boundary zone, but the fault undoubtedly has brought the two suites together and thus forms a major provincial boundary in southern California. We propose that this boundary was created by left-lateral displacements which projected the San Gabriel Mountains block westward relative to the Peninsular Ranges block along the ancestral Banning fault and correlative faults to the west.

Other workers have proposed significant left-slip on an east-trending fault zone--the middle Miocene Malibu Coast-Santa Monica zone--that probably extended through San Gorgonio Pass. Barbat (1958, fig. 2, p. 64) first suggested that the Santa Monica fault generated about 13 km of left-slip. Subsequently, Yerkes and Campbell (1971), Jahns (1973), and Campbell and Yerkes (1976) presented evidence for at least 90 km of left-slip during the middle Miocene (about 16 to 12 Ma). All of these workers extend the Malibu-Santa Monica system eastward through the Cucamonga fault (Barbat, 1958, fig. 1; Campbell and Yerkes, 1976, fig. 1; Jahns, 1973, fig. 5), and Jahns (1973, fig. 6-9, p. 166) extended the Malibu-Santa Monica-Cucamonga system eastward through San Gorgonio Pass by way of the Banning fault. We adopt Jahn's suggestion, and propose that the ancestral Banning generated 90 km of left-slip during middle Miocene time (about 16 to 12 Ma).

Juxtaposition of the Peninsular Ranges block against the San Gabriel Mountains block can be recognized clearly in San Gorgonio Pass, where the left-lateral relations have been modified only slightly by younger tectonism. West of San Gorgonio Pass, the provincial boundary between the Peninsular Ranges and San Gabriel Mountains blocks probably coincides with the inferred trace of the Banning fault that diagonals northwestward across the San Bernardino valley and is truncated by the San Jacinto fault. West of the San Jacinto, relations between the Banning and Malibu-Santa Monica faults are uncertain. Jahns (1973, figs. 6-9) believed that the Banning fault connected with the Cucamonga fault, which formed the eastern end of the Malibu-Santa Monica-Cucamonga system (Barbat, 1956; Campbell and Yerkes, 1976). Alternatively, we suggest that the Malibu-Banning fault in the vicinity of the southeastern San Gabriel Mountains is represented not by the Cucamonga fault but by poorly studied faults that extend up San Antonio Canyon and separate the San Gabriel Mountains block from batholithic granitoid rocks and prebatholithic metasedimentary rocks of the southeasternmost San Gabriel Mountains. Other workers have emphasized petrologic contrasts between rocks on either side of the San Antonio Canyon fault complex (Morton, 1975b, fig. 1; Ehlig, 1975, fig. 1; 1981, fig. 10-2; Dibblee, 1982, fig. 2, p. 132). We suggest that rocks east of this fault complex may be part of the Peninsular Ranges block that has been juxtaposed against the San Gabriel Mountains block by left-lateral displacements comparable to those that juxtaposed the two blocks in San Gorgonio Pass. However, in the southeastern San Gabriel Mountains, the course of the ancient Malibu-Banning fault has been deformed and obscured by younger right-lateral displacements on the San Gabriel fault and by northwest translation of the Peninsular Ranges block.

Right-lateral history.--Geologic relations among Tertiary sedimentary rocks in the San Gorgonio Pass area indicate that the ancestral Banning fault has at least 16 to 25 km of right-lateral displacement. Allen (1957, p. 329) suggested that the marine Imperial Formation south of the Banning fault has been displaced at least 11 km in a right-lateral sense from its cross-fault counterpart in the Whitewater area; differences in physical stratigraphy and foraminiferal biostratigraphy of the formation across the fault probably require even greater right-lateral separation (Allen, 1957, p. 329; J.C. Matti and K. McDougall, unpubl. data). The Painted Hill and Hathaway Formations (of Allen, 1957) south of the fault provide additional evidence for right-slip. These units contain 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, unpubl. data). When about 160 km of right-slip is restored on the San Andreas fault (discussed below), restoration of at least 16 to 25 km of right-slip on the Banning fault juxtaposes the Tertiary sedimentary rocks against the southern Chocolate Mountains where bedrock sources for some of their exotic clasts can be found.

The timing of right-slip is not bracketed tightly. Displacements occurred after 7.5 Ma because nonmarine sedimentary and volcanic rocks offset by the fault in San Gorgonio Pass are about that age (D. M. Morton, J. C. Matti, and J. L. Morton, unpubl. data). Considerable right-slip occurred after about 6 Ma because the Banning fault has displaced the Imperial Formation a minimum of 11 km and the unit is about 6 Ma old.[3] The western and central segments of the ancestral Banning fault do not offset

[3]The Imperial Formation in the Whitewater area is overlain by a basalt flow in the lower Painted Hill Formation that has yielded two whole-rock K/Ar age determinations of 6.04 ± 0.18 and 5.94 ± 0.18 Ma (J.C. Matti and J.L. Morton, unpubl. data).

Quaternary deposits, and the history of sediments in the San Timoteo Badlands south of the fault does not indicate right-slip on the fault during Plio-Pleistocene time (Matti and Morton, 1975, and unpubl.). These limited data suggest that the ancestral Banning fault generated at least 16 to 25 km of right slip between about 7.5 and 4 or 5 Ma.

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.

Quaternary history.--After the Banning fault was abandoned as a right-lateral strand of the San Andreas transform system 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 (J. C. Matti and B. F. Cox, unpubl. data); during late Quaternary time these gravels have been offset about 2 to 3 km into San Gorgonio Pass by right-lateral displacements on the Coachella Valley segment of the Banning fault (Sheet 2, F-F'). This figure probably represents the total amount of right-lateral offset 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'). Although the age span for these 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 neotectonic trace of the segment probably correponds to the position occupied by the paleotectonic strand of the ancestral Banning/San Gabriel fault in late Miocene and early Pliocene time.

San Andreas fault

Between the Tejon Pass region and the Imperial Valley, the San Andreas fault zone consists of three segments that have different degrees of structural complexity (fig. 1). We refer to these as the Mojave Desert, Coachella Valley, and Transverse Ranges segments.

Mojave Desert segment

The Mojave Desert segment of the San Andreas fault extends from Tejon Pass to the San Bernardino valley, where it overlaps and interacts with the San Bernardino strand of the Transverse Ranges segment. 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) 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). Lithologic contrasts across all strands of the Mojave Desert segment indicate that it forms a major tectonic boundary, but Barrows and others (1985) have not been able to document more than 102 km of right-lateral displacement within the zone.

Of interest to our work is the relationship between various strands of the Mojave Desert segment and multiple strands that we recognize in the Transverse Ranges segment. The Punchbowl fault in particular is relevant because it is one of the oldest strands in the Mojave Desert segment and its history and geologic setting may have bearing on the Wilson Creek strand of the Transverse Ranges segment. The Punchbowl fault originally was identified by Noble (1954a), who interpreted it as a reverse dip-slip fault but implied that it merged with the right-lateral San Jacinto fault by way of the Glen Helen fault (Noble, 1954b, pl. 5). Subsequently, Dibblee (1967a, 1968a) showed that the Punchbowl fault is a right-lateral fault that he interpreted as an older strand of the San Andreas fault zone. Dibblee (1967a, figs. 29, 72; 1968a, p. 263-264, fig. 1) indicated that the Punchbowl has as much as 48 km of displacement if the Fenner and San Francisquito faults are used as offset piercing points and if the Pelona Schist of Sierra Pelona is aligned with the Pelona Schist of Blue Ridge. Other authors propose similar displacements in the range of 40 to 45 km (Farley and Ehlig, 1977; Ehlig, 1981, fig. 10-4; Powell, 1981, p. 365-370; Barrows and others, 1985). Barrows and others (1985) indicate that the Punchbowl fault had an early Pliocene history and is one of the oldest strands of the Mojave Desert segment of the San Andreas fault. If the Punchbowl is an anastomosed strand of the San Andreas (sensu stricto) then it may be the offset counterpart of the Wilson Creek fault--the oldest strand of the Transverse Ranges segment.

Coachella Valley segment

In the Salton Trough the San Andreas fault zone breaks Quaternary and late Tertiary sediment of the Coachella Valley; older Tertiary and pre-Tertiary rocks juxtaposed by the fault are not widely exposed in this region. The surface expression of the modern fault 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, 1981, fig. 18-4; Lonsdale and Lawver, 1980, fig. 1; Johnson and Hill, 1982, fig. 6; Curray and Moore, 1984, figs. 1, 9).

In the southern Indio Hills the Coachella Valley segment of the San Andreas fault is joined by another right-lateral fault. 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, but we are not certain that his south branch is a throughgoing strand of the San Andreas. Instead, we suggest that it is a reactivated segment of the Banning fault (an idea shared by Dibblee, 1975a, p. 134). Our nomenclature reflects these interpretations (fig. 1). We refer to Dibblee's north branch as the Coachella Valley segment of the San Andreas fault, and 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.

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^o W, although Bilham and Williams (1985) identified alternating segments 9 to 14 km long that have trends of N 40^o W and N 48^o 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.

At its northwest end the regional strike of the Coachella Valley segment is deflected westward, and it splays into the multiple strands present in the Transverse Ranges segment 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 away from the south-central Transverse Ranges, 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 the community, 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.

Transverse Ranges segment

The Transverse Ranges segment of the San Andreas fault occurs within and adjacent to the San Bernardino Mountains. The segment 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 these 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 Transverse Ranges segment of the San Andreas fault 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.

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. The little-studied Wilson Creek fault has been mapped locally by Smith (1959), Dibblee (1964, 1968a, 1975a), Gibson (1964, 1971), and Matti and others (1983). Our use of the term Mission Creek fault follows Allen's (1957) usage, as refined by Ehlig (1977), Farley (1979), and ourselves (Matti and others, 1982a, 1983). 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 southeastern San Bernardino Mountains, where Matti and others (1983) identified two major strands within the Mission Creek fault zone. In this report we emphasize the significance of these two strands, identify them as the Wilson Creek and Mission Creek faults, respectively, and extend them elsewhere in the vicinity of the south-central Transverse Ranges.

Within crystalline rocks of the southeastern San Bernardino Mountains, the Wilson Creek and Mission Creek faults are closely spaced and bound a wide crush zone that traverses the range along a gently bowed, east-trending arc. 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 strand merges with the Mill Creek strand to form the Coachella Valley segment of the San Andreas fault. At the west end of their arc through the southeastern San Bernardino Mountains, the Wilson Creek and Mission Creek faults diverge and follow separate paths within and adjacent to the mountains.

Relations between the Wilson Creek and Mission 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 from a slice of far-travelled crystalline rocks of unknown provincial affinity; we refer to this slice as the Wilson Creek block. The Mission Creek fault bounds the Wilson Creek block on the south and separates it from a second terrane of far-travelled rocks similar to those in the lower and upper plates of the Vincent thrust in the eastern San Gabriel Mountains.

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 relations 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. Farley (1979) viewed the Pelona Schist body as a fault-bounded slice caught up between two branches of his Mission Creek fault zone, and he concluded that all bodies of Pelona Schist and associated crystalline rocks in the Raywood Flat area form a coherent package of rocks separated from rocks native to the San Bernardino Mountains by the north branch of his Mission Creek fault. Thus, Farley (1979) did not recognize two major strike-slip faults in the Raywood Flat area.

We concur that Pelona Schist and associated crystalline rocks in the southeastern San Bernardino Mountains are exotic to the region, but we believe these rocks represent two different assemblages bounded by two major strike-slip faults. Preliminary studies suggest that lower- and upper-plate rocks in our Wilson Creek block are different petrologically from their counterparts south of the Mission Creek fault. We interpret the Pelona Schist body not as a slice caught up within a right-lateral fault zone but as as a window in crystalline rocks of the Wilson Creek block; high-angle faults now bounding this window reflect reactivation and modification of a regional thrust surface (the Vincent-Orocopia-Chocolate thrust) that formerly had a low-angle geometry. Upper-plate rocks of the Wilson Creek block appear to be unlike those in either the San Bernardino Mountains or in the upper-plate terrane south of the Mission Creek fault--an interpretation requiring that these rocks are bounded by two major strike-slip 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 fault 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.--Directly northwest of 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. Near Wilson Creek, its namesake, the fault re-enters the San Bernardino Mountains and traverses Yucaipa Ridge before descending into Mill Creek Canyon. Our interpretations on Yucaipa Ridge are based on reconnaissance studies still in progress. There, the Wilson Creek fault separates crystalline rocks native to the San Bernardino Mountains from Tertiary sedimentary rocks assigned to the Potato Sandstone by Vaughan (1922) and Dibblee (1964) but referred to the Mill Creek Formation by Gibson (1964, 1971). Gibson's conclusion that these sedimentary rocks are exotic to the region requires that they must be separated from native crystalline rocks to the east by a major fault, and several faults having appropriate orientation occur within a broad zone of fractured and faulted rock that intervenes between the exotic and local terranes. Matti and others (1983) selected one of these faults as the master break. However, subsequent work by Demirer (1985) and ourselves indicates that relations on Yucaipa Ridge are more complex than we originally perceived, and are complicated by the presence of sedimentary rocks that may be locally derived in addition to those that are far-travelled. We have not yet documented the actual distribution of bounding faults within the Wilson Creek zone or the distribution of local and exotic crystalline and sedimentary terranes. However, a fault of regional significance must cross Yucaipa Ridge. Data available to us suggest that the master break may be slightly west of the position shown by Matti and others (1983), and may be represented by a fault that juxtaposes the Potato Sandstone and underlying basement rocks against sedimentary rocks that appear to have been deposited on basement rocks native to the San Bernardino Mountains.

In Mill Creek Canyon the Wilson Creek fault adopts a more westerly trend and converges with the younger Mill Creek fault. To the northwest, the fault continues along a trace that closely parallels the Mill Creek strand before diverging from it in the Cook Creek drainage near San Bernardino and exiting the San Bernardino Mountains. Along this segment the fault dips between 35^{o} and 65^{o} to the southwest. The 35^{o} 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; Gary Rasmussen, oral commun., 1984); however, we interpret it as a segment of the Wilson Creek fault that has acquired a low-angle geometry.

Between Mill Creek and the Cook Creek drainage, the fault that we identify as the Wilson Creek strand separates unnamed Tertiary sedimentary rocks that superficially resemble the Potato Sandstone (Morton and Miller, 1975, fig. 1d-1g, their unnamed unit of sandstone and conglomerate) from the Potato Sandstone and underlying crystalline rocks. Gibson (1964, 1971) and Dibblee (1968, fig. 3; 1975a, fig. 2; 1982, p. 159, fig. 7) mapped both sedimentary units as the Potato Sandstone, which they interpreted to have accumulated within a single depositional basin far to the southeast of the San Bernardino Mountains. Our recognition of the Wilson Creek fault, which we believe has large right-lateral displacement, between the Potato Sandstone and the unnamed sedimentary unit requires that the two deposits are not the same stratigraphic unit and did not accumulate in the same sedimentary basin. This interpretation is strengthened by the fact that the two sedimentary units have different clast assemblages and differ from one another in the details of their physical stratigraphy (Demerer, 1985; J. C. Matti, unpubl.).

Mission Creek fault.--In the southeastern San Bernardino Mountains, the Mission Creek fault separates crystalline rocks of the Wilson Creek block from distinctive 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 fault similar to the Vincent thrust. Lower-plate rocks are Pelona Schist that consists mainly of greenstone; upper-plate rocks are hornblende-bearing granitoid rocks and granitic gneiss that have strongly foliated and layered fabrics created by ductile and brittle deformation. Small bodies and lenses of Triassic Mount Lowe Granodiorite 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 including rocks of the southeastern San Bernardino Mountains within the San Gabriel Mountains block.

Between Banning Canyon and the Cajon Pass region, the Mission Creek fault cannot be located precisely because it is inactive and is covered by Holocene and most Pleistocene alluvial units. We infer the fault to lie along the southwest margin of the San Bernardino Mountains, southwest of the Wilson Creek fault—that is, in the same structural position it occupies in the southeastern San Bernardino Mountains. The Mission Creek fault in this region separates Pelona Schist underlying the San Bernardino Valley from granitoid and gneissic rocks of the Wilson Creek block to the north—the same role it plays in the southeastern San Bernardino Mountains.

Mill Creek fault

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 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, but Dibblee recognized that the fault (his north branch) must continue to the southeast. 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 hugs 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 herein, 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 may have 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 a relatively recent break which 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.

The Cajon Pass-Mill Creek segment 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 during Holocene and Recent 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.

The Mill Creek-Banning Canyon segment is characterized by its lack of clear continuous geomorphic expression, by its structural complexity locally, and by equivocal evidence for youthful activity: (1) Although the overall trend of the segment is relatively straight, between Mill Creek and Wilson Creek the fault has several conspicuous left steps and develops multiple traces. Between Wilson Creek and Banning Canyon the trace is not well defined and also may have left steps. (2) Scarps bound the left-stepping segments between Mill Creek and Wilson Creek, and right-laterally offset drainage lines are associated with en-echelon faults there. However, primary fault features generally are not common between Mill 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. (3) 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. (4) Preliminary studies (J. C. Matti and J. W. Harden, unpubl.) suggest that late Quaternary slip rates along the segment may not be as great as the 25 mm/year Holocene slip rate determined by Weldon and Sieh (1985) for the San Bernardino strand further to the northwest.

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, we question the origin of these scarps: 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 displacement 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 before it reaches San Gorgonio Pass.

Geologic history of the Transverse Ranges segment of the San Andreas Fault

The Transverse Ranges 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 Transverse Ranges segment.

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, workers in the southeastern San Bernardino Mountains have attempted to apportion this displacement among the various strands of the Transverse Ranges segment. On the basis of paleocurrent and clast-provenance studies, Gibson (1964, 1971) inferred that the Potato Sandstone on Yucaipa Ridge was deposited adjacent to the Orocopia Mountains and was juxtaposed against the San Bernardino Mountains by 120 km of right-slip on the Mill Creek fault. Dibblee (1968a, p. 269) concluded that, if 210 km of right-slip occurred along the San Andreas fault zone in the San Bernardino Mountains, then the largest movement probably occurred along the north branch (the 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 (1982, 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 Potato Sandstone 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 between Banning Canyon and San Gorgonio Pass. This leaves only the San Jacinto and Banning faults to take up the missing 100 km--and neither fault qualifies because Sharp (1967) showed that the San Jacinto has no more than 25 or 30 km of displacement and because the Banning did not generate right-lateral displacements at the same time as the San Andreas (sensu stricto) and does not figure into the 210-km reconstruction proposed by Crowell (1962).

In his study of the 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 north branch of the San Andreas fault. Probable cross-fault counterparts include crystalline rocks of the San Gabriel Mountains block northeast of San Gorgonio Pass and similar rocks south of Mammoth Wash in the Chocolate Mountains (Dillon, 1975, p. 59-60, 351-353), and the Miocene Coachella Fanglomerate in the Whitewater area (Peterson, 1975) and the Conglomerate of Bear Canyon in the southern Chocolate Mountains (Dillon, 1975, p. 341-346). Dillon also suggested that the shoreline for the marine Imperial and Bouse Formations has been offset between the two regions. Dillon's (1975) displacement on the north branch of the San Andreas (180±20 km) is considerably greater than the displacements proposed by Gibson and Dibblee (96 to 120 km), but the cross-fault correlations leading to both displacements seem equally attractive.

The pioneering studies by Gibson and Dibblee in the southeastern San Bernardino Mountains have been updated by more recent studies that have reinterpreted the bounding faults between distinctive basement terranes and proposed different displacements for the faults. Ehlig (1977), Farley (1979), and Matti and others (1983) showed that the Mill Creek fault (Dibblee's north branch) does not form a major break between crystalline rocks as Dibblee (1968a, 1975a, 1982) 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 fault. Building on Ehlig's (1977) earlier work, Farley (1979) demonstrated that the major lithologic break between crystalline rocks is formed by Allen's (1957) Mission Creek fault zone—an interpretation we accept and refine in this report. Farley (1979, p. 120-129) cited Dillon's (1975) cross-fault correlations to suggest that the Mission Creek and Mill Creek faults together generated about 175 km of right-slip, with the Mill Creek having only a small fraction of this total 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 (in press) 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 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 offset by the fault. We adopt the 160-km displacement, and apportion it between the four strands of the Transverse Ranges segment of the San Andreas fault: 3 km on the San Bernardino strand, 8 km on the Mill Creek strand, and about 150 km on the Wilson Creek and Mission Creek strands.

Our proposal that the San Bernardino strand has no more than 3 km of displacement 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 (B. F. Cox and J. C. Matti, unpubl.); since their deposition the gravels have been displaced no more than 3 km by the San Bernardino strand. 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 or S3 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.

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 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'). Proctor (1968) originally assigned the Desert Hot Springs gravels questionably to the Miocene Coachella Fanglomerate, but they probably are Quaternary. 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 cross-fault counterparts.

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.

The Wilson Creek and Mission Creek faults together have about 150 km of displacement, obtained by subtracting 11 km of combined displacement on the San Bernardino and Mill Creek strands from about 160 km of total displacement on all strands (Matti and others, in press). At present we cannot apportion the 150 km between the two strands, although we can discuss problems and constraints and isolate the most likely possibilities. Two cross-fault correlations ultimately may assist in determining the amount of slip on the two strands: (1) Dillon's (1975) proposal that crystalline rocks of the San Gabriel Mountains block and overlying Tertiary sedimentary rocks have been displaced from cross-fault counterparts in the southern Chocolate Mountains, and (2) Gibson's (1964, 1971) proposal that the Potato Sandstone has been displaced from its original depositional position adjacent to the Orocopia Mountains.

Dillon's (1975) correlation of rocks between the southeastern San Bernardino Mountains and the southern Chocolate Mountains seems reliable because it is based on favorable comparisons between several distinctive rock types (Dillon, 1975, fig. 68). This correlation is critical to the movement history of the Transverse Ranges segment of the San Andreas fault because rocks of the San Gabriel Mountains block outboard of the Mission Creek fault are the farthest travelled of any exotic terranes within the Transverse Ranges segment, and thus record the full displacement on the San Andreas fault (except for 3 km on the San Bernardino strand and Coachella Valley segment of the Banning fault--a displacement that passes outboard of this part of the San Gabriel Mountains block). It is not a coincidence that the lower end of Dillon's 180±20 km displacement for the Coachella Valley segment of the San Andreas overlaps the high end of the 160±10 km displacement proposed for the Mojave Desert segment (Matti and others, in press): both displacement are based on attractive cross-fault correlations that independently yield 160 to 180 km of total displacement. We favor the smaller figure and thus prefer the low end of Dillon's 180±20 range.

The Potato Sandstone and underlying crystalline rocks of the Wilson Creek block provide a direct basis for determining the amount of displacement on the Wilson Creek fault. However, it presently is not possible to evaluate whether these rocks can be used for cross-fault correlation.

Gibson (1964, p. 44-48; 1971) cited several lines of evidence for his proposal that the Potato Sandstone was deposited in the vicinity of the Orocopia Mountains, but he emphasized locally abundant clasts of Pelona-type schist in the formation that he suggested were derived from the Orocopia Schist of the Orocopia Mountains. Recently, Demirer (1985) used facies analysis and paleocurrent studies to show that the sedimentary fill of the Potato Sandstone, including beds rich in Pelona Schist, largely was transported from directions incompatible with sources in the Orocopia Mountains. Thus, the basis for Gibson's restoration of the Potato Sandstone to the vicinity of the Orocopia Mountains has been called into question. Underlying crystalline rocks of the Wilson Creek block presently are no better suited for cross-fault correlations. These rocks are hornblende- and biotite-bearing granitoid and gneissic rocks that are demonstrably exotic to the San Bernardino Mountains, but whose generalized composition presently precludes a specific match with terranes on the opposite side of the San Andreas fault. On the crest of Yucaipa Ridge the granitic and gneissic rocks contain small bodies of anorthositic rock petrographically similar to Precambrian anorthosite in the San Gabriel and Orocopia Mountains (Sheet 1, A; D. M. Morton and J. C. Matti, unpubl.); these bodies ultimately may assist in cross-fault correlation of the Wilson Creek block. Smith (1959) mapped a small body of Pelona Schist on the south flank of Yucaipa Ridge that he thought was overlain depositionally by the Potato Sandstone. Although this interpretation is reasonable, the outcrop relations are not conclusive and the Pelona Schist body may be a syndepositional landslide sheet intercalated with sediment of the Potato Sandstone. Whatever its origin, this schist body indicates that the Potato Sandstone was deposited either on Pelona Schist or near a body of Pelona Schist that cropped out to the west or southwest of the depositional basin. In short, although the Potato Sandstone and underlying crystalline rocks of the Wilson Creek block may have originated near the Orocopia Mountains, this cross-fault correlation has not been proven.

If Gibson (1964, 1971) and Dillon (1975) both are correct, then the Wilson Creek block and overlying Potato Sandstone are not as far travelled as the San Gabriel Mountains block, and do not reconstruct as far south along the Coachella Valley segment of the San Andreas fault. These relations can be used to apportion the 150-km total displacement between the Wilson Creek and Mission Creek faults--assuming they coalesce to form the Coachella Valley segment of the San Andreas. About 110±20 km of displacement on the Wilson Creek fault is needed to offset the Wilson Creek block from the vicinity of the Orocopia Mountains to the southeastern San Bernardino Mountains; this displacement simultaneously moved the San Gabriel Mountains block from the southern Chocolate Mountains to a position farther northwest along the Coachella Valley segment. The Wilson Creek block became stranded adjacent to the San Bernardino Mountains when the Wilson Creek fault was deformed and abandoned, but the Mission Creek fault bypassed this bottleneck and displaced the San Gabriel Mountains block an additional 40±20 km to the northwest and juxtaposed it against the stranded Wilson Creek block--a juxtaposition observed today in the southeastern San Bernardino Mountains. Subsequently, the combinded San Gabriel and Wilson Creek blocks were displaced together an additional 8 km by the Mill Creek fault.

A different reconstruction of the Wilson Creek block would result if the Wilson Creek fault has been offset from the northwest termination of the Punchbowl fault in the San Gabriel Mountains. The two faults would have the same displacement--about 40 to 45 km, if estimates for displacement on the Punchbowl fault are correct (Dibblee, 1967a, 1968a; Farley and Ehlig, 1977; Barrows and others, 1985)--and restoration of only that much right-slip on the Wilson Creek fault would juxtapose the Wilson Creek block and Potato Sandstone midway along the west margin of the little San Bernardino Mountains instead of adjacent to the Orocopia Mountains. Correlation of the Punchbowl and Wilson Creek faults is appealing based on what is known about their geologic setting and history: both faults are old right-lateral strands that have deformed traces, and according to Barrows and others (1985) the Punchbowl fault was active in the early Pliocene at the time we believe the Wilson Creek fault was active. In this scenario the amount of displacement on the Wilson Creek and Mission Creek faults is reversed: the two strands have about 40 and 110 km of displacement, respectively, rather than 110 and 40 km of displacement if the Wilson Creek block and Potato Sandstone reconstruct to the Orocopia Mountains region. However, this reversal does not violate the fact that the San Gabriel Mountains block is farther travelled than the Wilson Creek block: in either scenario the San Gabriel Mountains block reconstructs to the southern Chocolate Mountains as required by Dillon (1975), but the Wilson Creek block reconstructs to a different position. This example of palinspastic legerdemain illustrates the fact that the Wilson Creek block is a poorly studied fault slice whose cross-fault counterpart has not been proved. Until these problems are resolved, the 150 km of combined displacement on the Wilson Creek and Mission Creek faults cannot be confidently apportioned between them.

Age of faulting

Wilson Creek and Mission Creek faults.--Our conclusion that the four strands of the Transverse Ranges 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 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 Imperial and Painted Hill Formations, which are about 6 m.y. old and younger (see footnote 3). 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 indicate the same displacement requires that the San Andreas fault offset 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), 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. From Banning Canyon northwest to 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, then the Mill Creek fault generated all of its right-lateral displacement during late Pleistocene time. Faulting occurred more recently than about 0.5 Ma, which is a 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 no older than 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 y. 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). 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). 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.

Synthesis

Available data lead to a preliminary history of the San Andreas fault in the vicinity of the Transverse Ranges:

(1) Following inception of the San Andreas fault 4 or 5 m.y. ago, right-slip on the Wilson Creek fault juxtaposed exotic crystalline and sedimentary rocks of the Wilson Creek block against the San Bernardino Mountains (fig. 2A). Rocks native to the San Bernardino Mountains, including Triassic megaporphyritic monzogranite discussed by Matti and others (in press), were displaced to the northwest by these offsets and the Potato Sandstone was juxtaposed against rocks native to the San Bernardino Mountains. During this period, the Wilson Creek 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 fault terminated when it was deformed into a sinuous trace and was bypassed by the Mission Creek fault (fig. 2B). 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. 2C). Like the Wilson Creek fault, 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. 2D), 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. 2E), and generated about 8 km of right-lateral displacement during the late Pleistocene (after about 0.5 m.y.B.P.). 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. 2F). 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 Plio-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). 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 alternated between the E-W and vertical axes. Allen proposed that right-slip on San Andreas-type faults has predominated when the intermediate stress is oriented vertically, but thrust faulting (and presumably left-slip on structures like the Pinto Mountain fault) has predominated when the intermediate stress is 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 generalized model, 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; 1982). 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 had 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; 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. However, because we presently cannot determine if the Wilson Creek fault was active only for a short period during the early Pliocene or for a longer period that spanned all of the Pliocene, we cannot demonstrate one-to-one linkage between initial deformation of the San Andreas fault in the Transverse Ranges and initial orogenic uplift of the San Bernardino Mountains. It is appealing to have the Wilson Creek fault generate about 110 km of displacement at 35 mm/year during the Pliocene (5 to 2 m.y.), and then be deformed and succeeded by the Mission Creek fault about 2 m.y. ago when initial uplift of the mountains commenced. The Mission Creek fault then would have generated about 40 to 45 km of displacement at 35 mm/year during the early Pleistocene (2 to about 0.8 m.y) before it, too, would have been abandoned. Thus, a single period of strand deformation beginning about 2.0 m.y. ago would coincide neatly with a single period of orogeny in the San Bernardino Mountains beginning at about the same time. Unfortunately, this scenario is voided if the Wilson Creek fault has been offset from the Punchbowl fault in the San Gabriel Mountains. According to Barrows and others (1985) the Punchbowl is an old strand of the San Andreas that was deformed and abandoned during the early Pliocene; if the Wilson Creek and Punchbowl faults formerly were continuous and had a relatively short-lived history before being deformed and abandoned at the latitude of the southeastern San Bernardino Mountains, then initial strand deformation did not coincide with initial uplift of the San Bernardino Mountains (which was a later event according to Meisling, 1984). We cannot choose between options like these that require more information before they can be demonstrated.

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 Wilson Creek fault may have bearing on the history of the Pinto Mountain fault. In the southeastern San Bernardino Mountains the Wilson Creek fault has a concave-northeast trace that occurs outboard of crystalline rocks native to the region. This curving geometry apparently was achieved as a bulge of local basement was projected west and southwest across the path of the Wilson Creek fault during the late stages of its activity—an event that accompanied deformation of the strand into its sinuous trace (fig. 2B,C; fig. 3). 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 Wilson 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 Wilson Creek strand into a curved trace (fig. 3). When the curvature became too great to sustain right-slip, the Wilson Creek was succeeded by the Mission Creek strand (fig. 2C). It is unclear whether left-slip on the Pinto Mountain fault continued throughout the history of the Mission Creek fault, 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. 2D). 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. 3): 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 Wilson Creek and Mission Creek faults were 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 Transverse Ranges 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). It is possible that the long-term slip rate for the Transverse Ranges segment of the San Andreas fault has varied through time, but such a scenario can be documented only when the timing and amount of right-lateral displacements on the Wilson Creek and Mission Creek strands of the segment are better understood.

San Jacinto fault

Within the Peninsular Ranges block the San Jacinto fault separates the San Jacinto Mountains and San Timoteo Badlands from the Perris block. In the San Jacinto Mountains the fault forms a narrow zone that locally is complicated by anastomosed strands and by thrust faults (Sharp, 1967, 1972). To the northwest, the fault enters the San Jacinto Valley and splays into branches that appear to represent major right and left steps in the zone. An eastern right-stepping branch hugs the northeast side of the Valley and locally forms scarps in late Quaternary deposits; however, the 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. Although the northeast branch has stepped right away from the main zone in the San Jacinto Mountains, between San Jacinto and U.S. Highway 60 it appears to be complicated by several left steps. To the west, the Casa Loma fault forms a left-stepping branch of the San Jacinto fault that hugs 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 may step right (east) onto the eastern branch of the San Jacinto zone.

Between the San Jacinto Valley and the San Gabriel Mountains the San Jacinto fault offsets Quaternary alluvial units and sedimentary rocks. In the Reche Canyon area the fault traverses strongly folded Quaternary deposits of the San Timoteo Badlands, and has a pronounced bow convex to the west; 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 breaks 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.

Where it enters the southeastern San Gabriel Mountains, the San Jacinto fault splays into several strands that appear to curve westward into the San Gabriel Mountains without joining the San Andreas fault (Morton, 1975a,b, 1976). Some workers suggest that the San Jacinto fault connects directly with the Punchbowl fault and ultimately feeds into the Mojave Desert segment of the San Andreas (for example, see Ehlig, 1981, fig. 10-2). This interpretation leads to the idea that total displacement on the San Andreas includes displacements on the San Jacinto (Ehlig, 1982, p. 375; Weldon, 1984). However, Dibblee (1968a, fig. 1, p. 266; 1975b, p. 156) and Morton (1975a; 1975b, fig. 1, p. 175) concluded that the San Jacinto fault cannot be mapped into either the Punchbowl or San Andreas faults, and that the Punchbowl fault merges with the San Andreas along the western base of the San Bernardino Mountains. Thus, it is unclear whether total slip on the San Jacinto fault has contributed to total slip on the San Andreas fault northwest of the Cajon Pass region.

In the vicinity of the San Gabriel Mountains the San Jacinto fault does not form primary fault features in late Quaternary alluvium. However, the Glen Helen fault forms scarps and sag ponds in Holocene deposits (Sharp, 1972, map sheet 3; Morton and Matti, in press). The Glen Helen fault may be the active strand of the San Jacinto fault in the Cajon Pass/San Gabriel Mountain region, although Metzger and Weldon (1983) documented about 2 mm of late Quaternary slip on the Lytle Creek fault which thus may represent a modern strand of the San Jacinto zone.

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). However, in the San Gabriel Mountains Morton (1975b, p. 175) documented no more than half this displacement.

COMPRESSIONAL FAULT SYSTEMS

San Gorgonio Pass fault complex

We apply the name San Gorgonio Pass fault complex 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 system 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 complex 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 complex 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. Traced westward, faults of the San Gorgonio Pass complex 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 compression) suggest that the fault systems are mechanically interelated.

Faults of the San Gorgonio Pass complex 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 500 to 1000 years ago. The western part of the fault zone between Beaumont and Calimesa appears to be the locus of late Pleistocene activity; Holocene faults tend to occur in the eastern part of the zone between Beaumont and Whitewater. 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, in press). 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, in press).

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 further south at the mountain front and form conspicuous scarps in young Pleistocene and Holocene alluvial fans. 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 complex

We apply the name Beaumont Plain fault complex 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 horst-and-graben complex to a system of normal dip-slip faults that occurs 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, 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 system 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, in press, b). The faults, which break Holocene deposits, probably have dip-slip displacements. 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), Williams and others (1984), Corbett and Hearn (1984), Sanders and Kanamori (1984), and Webb and Kanamori (1985).

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, hypocenters for this earthquake and for associated shocks did not align with the surface trace of the fault but instead formed a seismicity 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 suggested 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.

Green's (1983) 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. (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, 1984a; 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-dipslip mechanisms with a left-lateral component occur in the vicinity of the Crafton Hills horst-and-graben complex (also see Nicholson and others, 1983, 1984a), and normal mechanisms occur locally within the San Bernardino valley region (for example, 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, 1984). (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 J. C. Tinsley and J. C. Matti indicate relatively high rates of convergence in excess of 10 mm/year.

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.

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 farthér southeast in the vicinity of Highland.

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.). 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 6.5 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 (1976) 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 the long-term Quaternary rate of 8 to 12 mm/year Sharp (1981) determined 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. 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 region 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.

Are there left and right steps in the modern San Andreas fault?

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. 3). 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 Transverse Ranges 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. 4) 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 Transverse Ranges 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 a 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 largely has been 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. 4). 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. 4). (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 (1975b, 1976) has 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, 1983) that may define the boundaries of clockwise-rotating blocks (Nicholson and others, 1984a). 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. 4). 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. Thus, the 25 mm/year slip rate determined by Weldon and Sieh (1985) for the San Bernardino strand in Cajon Pass may not have characterized the late Quaternary history of the fault in the Crafton Hills-Oak Glen region—an hypothesis currently being evaluated by J. C. Matti and J. W. Harden (in progress). 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 (1984a). During the period between large earthquakes on either the San Jacinto or San Andreas faults (the interseismic period of Nicholson and others, 1984a, and in press), 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, in press; 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 Transverse Ranges 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 150 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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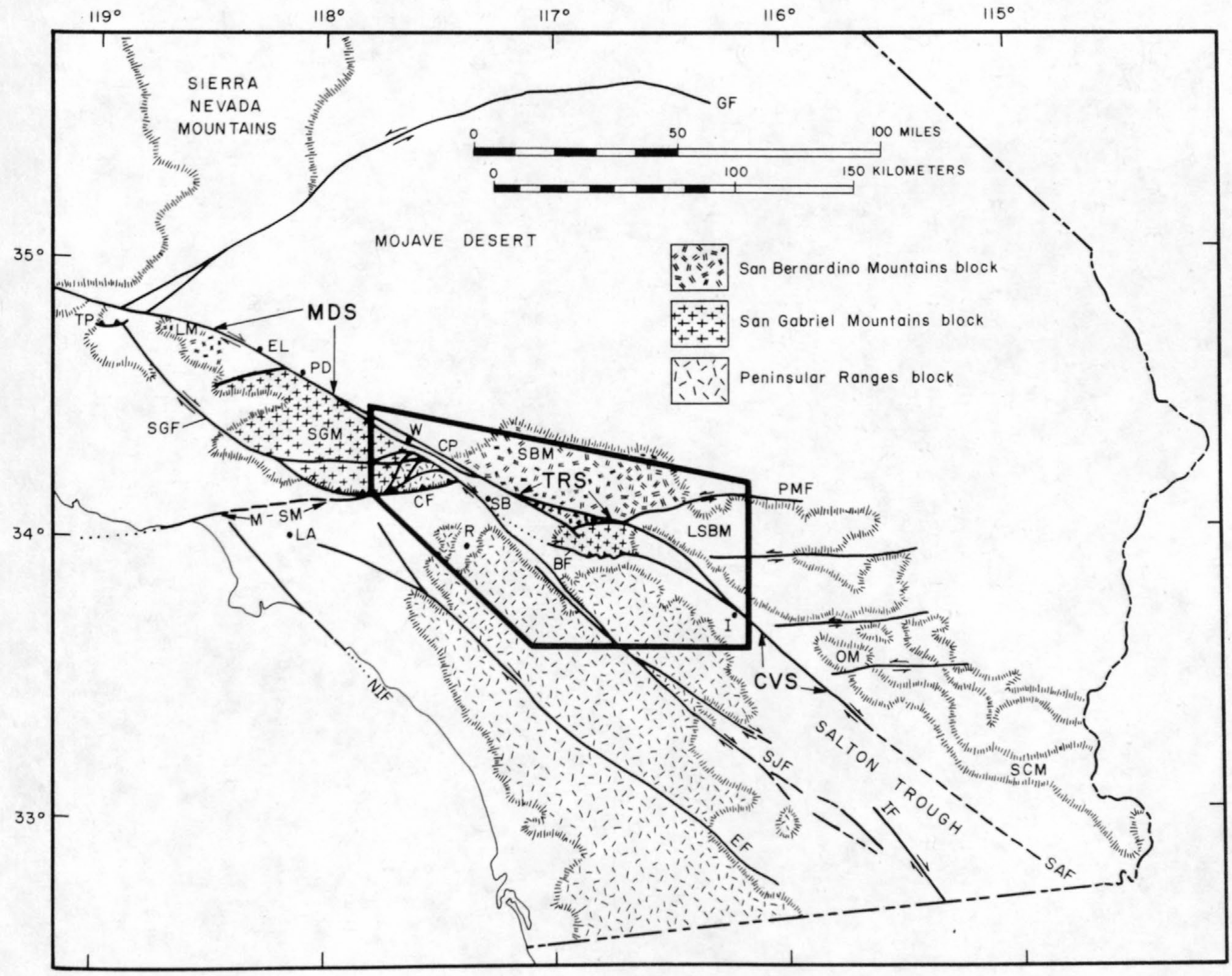

Figure 1.--Index map showing location of study area and distribution of major faults. The dashed trace of the Coachella Valley segment of the San Andreas fault in the southern Salton Trough indicates its probable course during much of Pliocene and Pleistocene time. The modern neotectonic trace of the fault can be recognized only where its trace is shown by a solid line. CF, Cucamonga fault; CP, Cajon Pass; CVS, Coachella Valley segment, San Andreas fault; EF, Elsinore fault; EL, Elizabeth Lake; GF, Garlock fault; LA, Los Angeles; LM, Liebre Mountain; LSBM, Little San Bernardino Mountains; MDS, Mojave Desert segment, San Andreas fault; M-SM, Malibu-Santa Monica fault zone; NIF, Newport-Inglewood fault; OM, Orocopia Mountains; PD, Palmdale; PMF, Pinto Mountain fault; R, Riverside; SAF, San Andreas fault; SB, San Bernardino; SBM, San Bernardino Mountains; SCM, southern Chocolate Mountains; SGF, San Gabriel fault; SGM, San Gabriel Mountains; SJF, San Jacinto fault; TP, Tejon Pass; TRS, Transverse Ranges segment, San Andreas fault; W, Wrightwood.

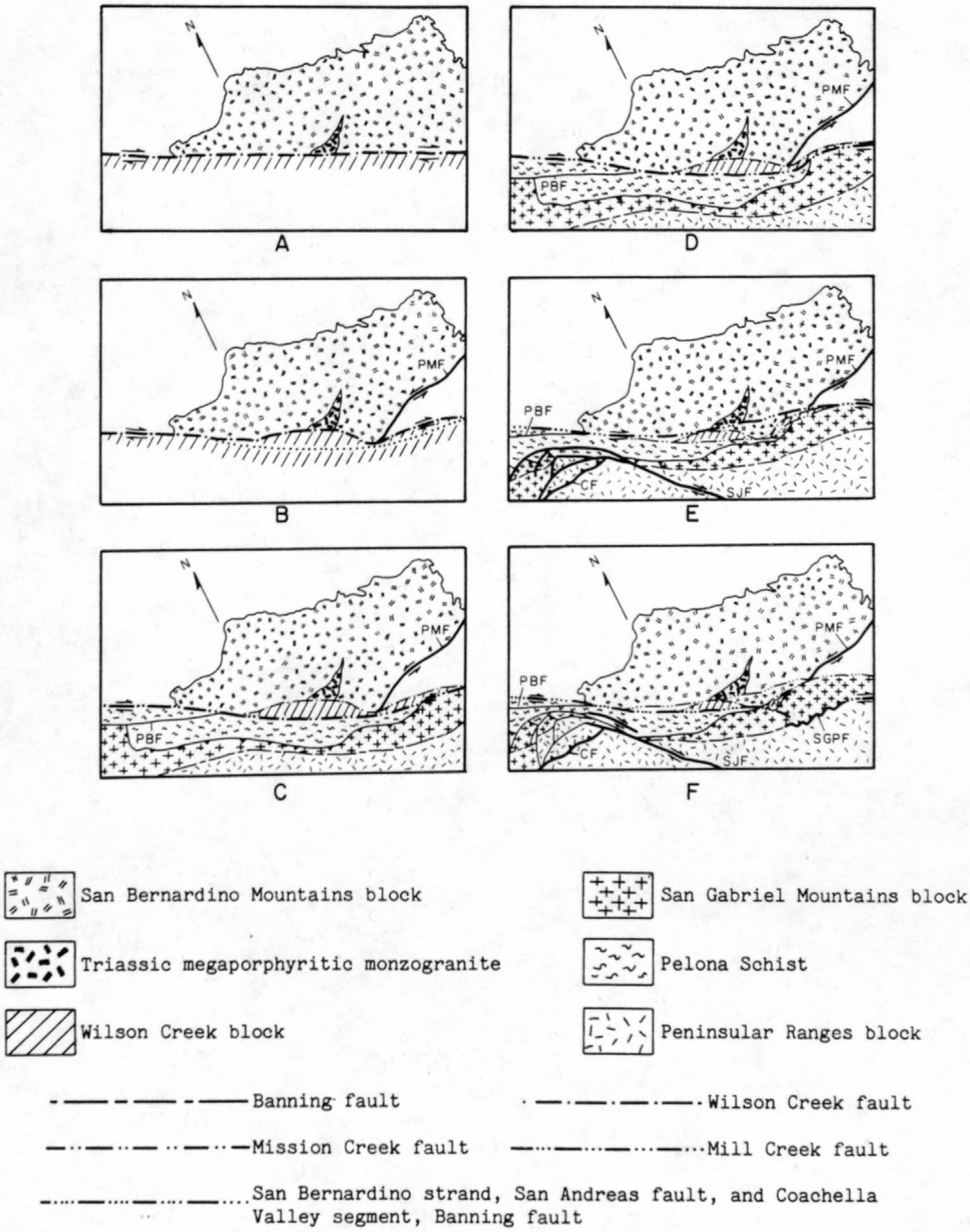

Figure 2.--Schematic drawings summarizing the history of the San Andreas fault in the vicinity of the central Transverse Ranges. Heavy lines indicate active faults; lighter lines indicate inactive faults. CF, Cucamonga fault; PBF, Punchbowl fault. (A) Unknown amount of right-slip on the Wilson Creek fault juxtaposes the Wilson Creek block against the San Bernardino Mountains block; the total extent of the Wilson Creek block and its relations with other terranes are not known. (B) The Wilson Creek fault is compressed into a curving trace and the strand has locked up. Dotted line shows the future trace of the Mission Creek fault. (C) The Mission Creek fault evolves outboard (west) of the abandoned Wilson Creek fault and generates an unknown amount of right-slip that juxtaposes the San Gabriel Mountains block against the Wilson Creek and San Bernardino Mountains blocks. (D) The Mission Creek fault 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. 3). (E) The Mill Creek fault evolves inboard of the locked up Mission Creek fault, and generates right-lateral displacements which truncate the westward projection of the San Bernardino Mountains block and displace it about 8 km to the northwest. The San Jacinto fault (SJF) also evolves as the Mission Creek fault locks up. (F) The Mill Creek fault is locked up by continued left-slip on the Pinto Mountain fault, leading to the modern neotectonic setting where slip 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.

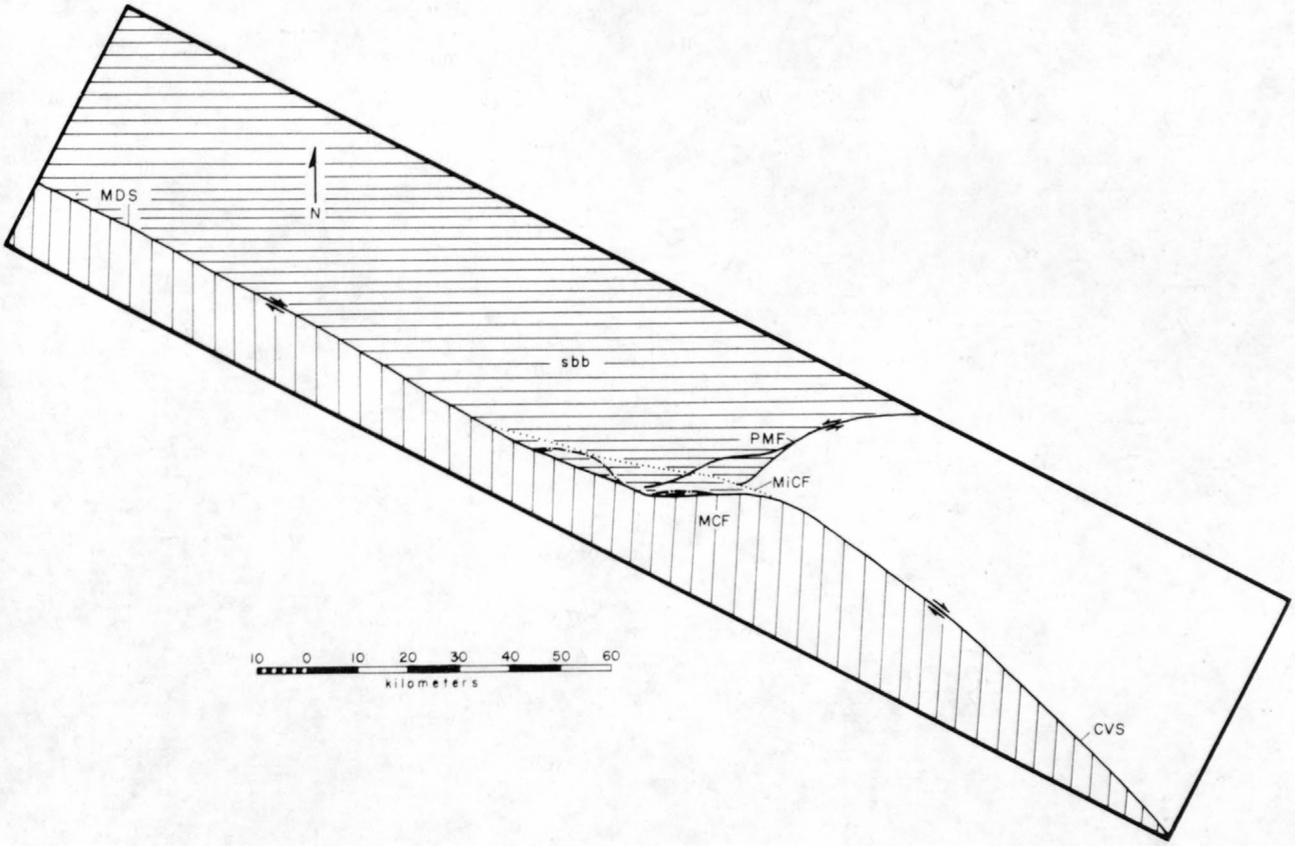

Figure 3.--Diagram illustrating left step that offsets the Coachella Valley and Mojave Desert segments of the San Andreas fault. The Mission Creek fault (MCF) has generated all of its right-lateral displacement and soon will be abandoned and succeeded by the Mill Creek fault (MiCF), which will develop along the dotted trace and generate 8 km of displacement. 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 offset the Mojave Desert (MDS) and Coachella Valley (CVS) segments of the San Andreas fault by about 15 km--the amount of left-slip on the Pinto Mountain fault (Dibblee, 1968b). Exotic rocks of the Wilson Creek block, originally juxtaposed against the San Bernardino Mountains block by right-slip on the Wilson Creek fault, became attached to the San Bernardino Mountains block once they were bypassed by the Mission Creek fault; 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.

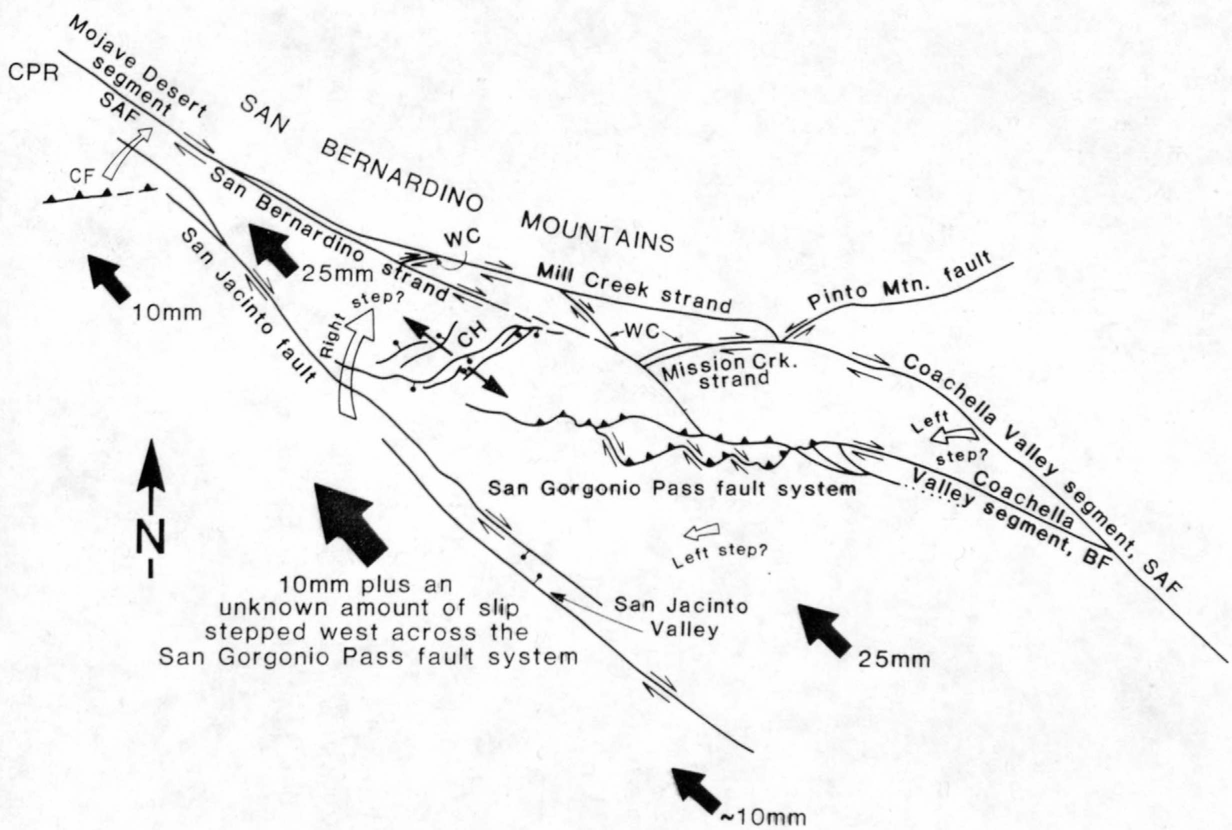

Figure 4.--Schematic diagram illustrating relations between faults and crustal blocks in the vicinity of the south-central Transverse Ranges. Large solid arrows indicate the relative motion of crustal bloicks; large hollow arrows indicate lateral transfer of slip. Small solid arrows indicate crustal extension in the Crafton Hills fault complex. BF, Banning fault; CF, Cucamonga fault; CH, Crafton Hills; CPR, Cajon Pass region; SAF, San Andreas fault; WC, Wilson creek strand, San Andreas fault. Ten mm annual-slip rate on the San Jacinto fault is an average of the 8 to 12 mm rate determined by Sharp (1981).

POCKET CONTAINS:
2 ITEMS