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EVOLUTION OF THE SAN ANDREAS FAULT[1]

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INTRODUCTION

The modern San Andreas fault forms an 1100-km transform link between a transform-transform-trench triple junction off Cape Mendocino and a system of seafloor spreading axes and transform faults in the Gulf of California (Figure 1). As a transform fault, the San Andreas is commonly represented as the boundary between the North American and Pacific plates, but actually it is only one fault in a complex system of faults (Figure 2) that absorbs the relative motion between the two plates. The transform fault paradigm satisfactorily explains the existence of the San Andreas fault as a consequence of relative plate motion between the two plates, but because most transform faults are relatively simple oceanic structures, the paradigm provides little insight into the intracontinental evolution of the complex San Andreas system. On the other hand, the geologic record along the San Andreas fault system not only tells of its evolution, but also illuminates how the various parts of the system may have functioned in the evolving plate boundary.

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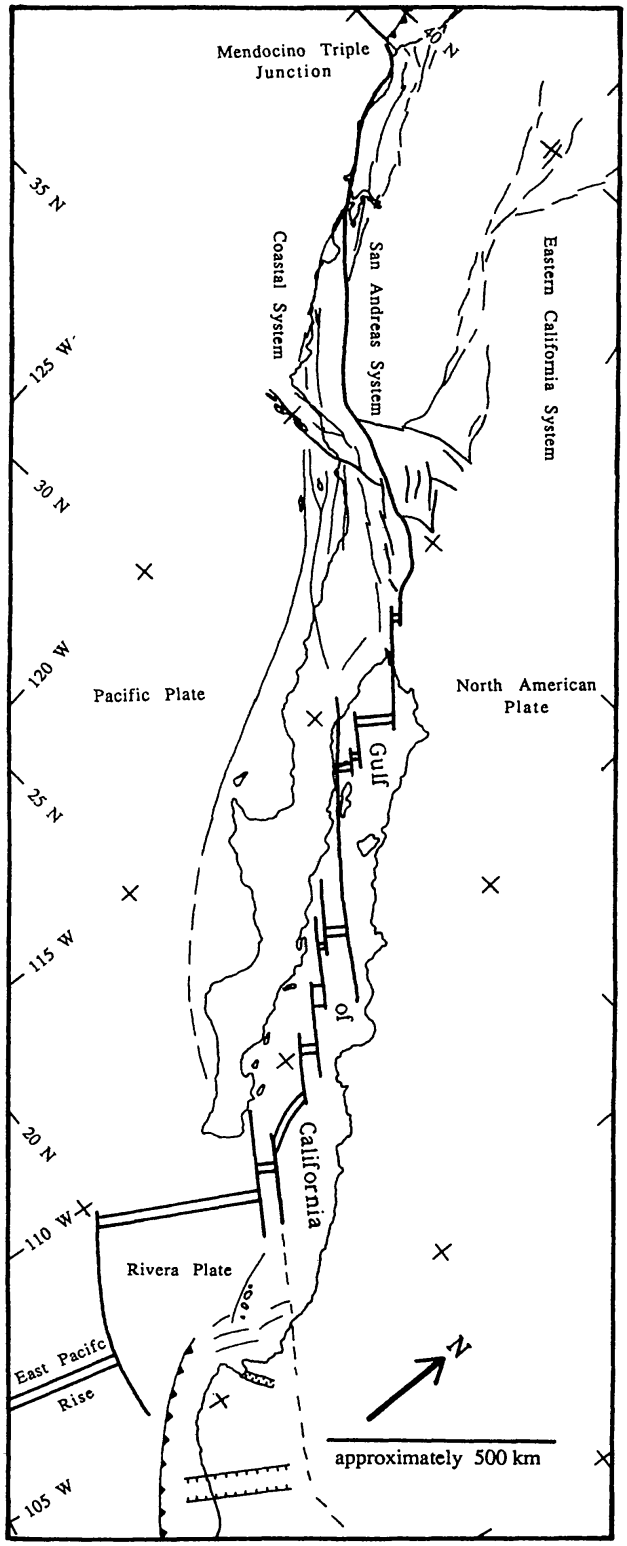

Figure 1 Plate tectonic setting for the modern San Andreas fault. After Humphreys & Weldon (1991).

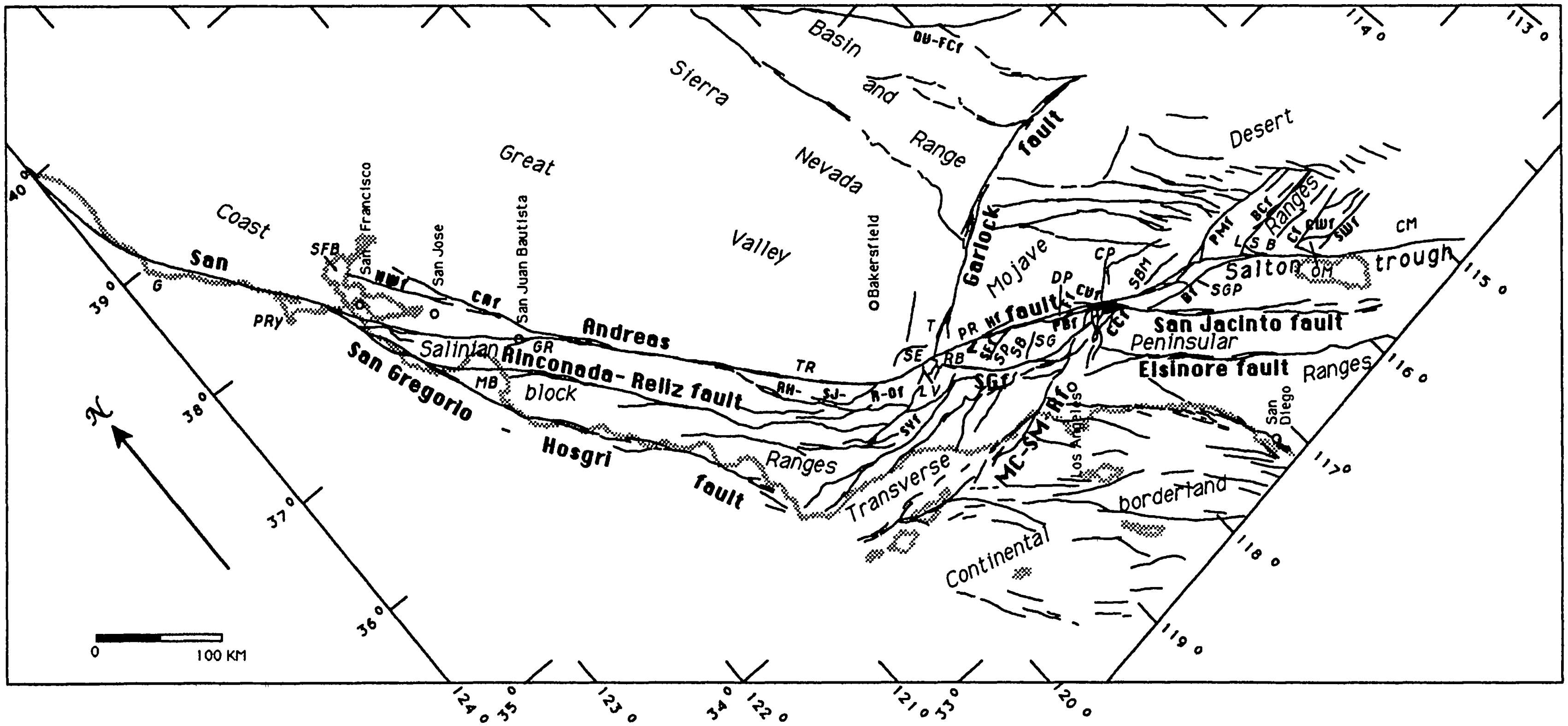

Figure 2 San Andreas fault system in southern and central California (after Powell 1992b). Faults: Bf, Banning fault; BCf, Blue Cut fault; Cf, Chiriaco fault; CAf, Calaveras fault; CCf, Cucamonga fault; CVf, Cajon Valley fault; CWf, Clemens Well fault; DV-FCf, Death Valley–Furnace Creek fault; Ff, Fenner fault; Hf, Hitchbrook fault; HWf, Hayward fault; MC-SM-Rf, Malibu Coast–Santa Monica–Raymond fault; PBf, Punchbowl fault; PMf, Pinto Mountain fault; RH-SJ-R-Of, Red Hills–San Juan–Russell–Ozena fault; SFf, San Francisquito fault; SGf, San Gabriel fault; SWf, Salton Creek fault; SYf, Santa Ynez fault. Physiographic features: *CM*, Chocolate Mountains; *CP*, Cajon Pass; *DP*, Devil's Punchbowl; *G*, Gualala; *GR*, Gabilan Range; *L*, Liebre Mountain; *LSB*, Little San Bernardino Mountains; *LV*, Lockwood Valley; *MB*, Monterey Bay; *OM*, Orocopia Mountains; *PR*, Portal Ridge; *PRy*, Point Reyes; *RB*, Ridge basin; *SB*, Soledad basin; *SBM*, San Bernardino Mountains; *SE*, San Emigdio Mountains; *SFB*, San Francisco Bay; *SG*, San Gabriel Mountains; *SGP*, San Gorgonio Pass; *SP*, Sierra Pelona; *T*, Tehachapi Mountains; *TR*, Temblor Range.

In the past decade, continuing study of displacement, timing of movement, and slip rate on the various faults of the San Andreas system, and of the rate of relative motion between the North American and Pacific plates has yielded a rapidly growing body of evidence that is inconsistent with the widely cited history of the fault system. In this review, we summarize the evidence, published and in press, that is incompatible with the prevailing consensus model and that forms the basis for a new consensus model. We emphasize results from the study of overall displacement, slip rate, and palinspastic restoration of the San Andreas fault system in southern and central California [see papers in Powell et al (1992)]; we also take note of new calculations of the rate of relative motion between the North American and Pacific plates based on seafloor magnetic anomalies in the Gulf of California and on orbital geodetic measurements (DeMets et al 1990, Ward 1990, Ness et al 1991).

The past decade has also seen much research on topics that relate to the history of the San Andreas system. Much recent work has focused on the role of evolving geometric complexities and secondary structures in earthquake segmentation and nucleation (Schwartz & Coppersmith 1984, Sieh et al 1989, Weldon & Springer 1988, Jones 1988), on the strength of the fault in relation to the orientation of regional stress (Zoback et al 1987, Mount & Suppe 1987), on the kinematics of rotated blocks (Luyendyk et al 1985, Hornafius et al 1986, Carter et al 1987), and on the postulated existence of exotic terranes in California (Champion et al 1984, Beck 1986, Butler et al 1991). This research has fostered debate about the age, style, and role of structures associated with the San Andreas system [see papers in Wallace (1990) and Zoback & Lachenbruch (1992)]. While we cannot address the findings of all these studies in this short review, we present a history for the San Andreas system that provides a new perspective and a better foundation from which to address these and other topics.

We begin this review with a history of study of the San Andreas fault system since 1950, where we summarize the findings that culminated in the prevailing model for the fault system's evolution and contemporaneous findings that are incompatible with the model. We then briefly describe the key evidence that provides the impetus and basis for developing a new model for the evolution of the fault system. Finally, we examine the evolving role of the San Andreas fault in the plate boundary from the perspective of this new model.

DEVELOPMENT OF CONCEPTS SINCE 1950

Modern study of the San Andreas fault system began in the early 1950s with the initial documentation of large right-lateral displacement—tens of kilometers on the San Gabriel fault (Crowell 1952) and hundreds of kilometers on the San Andreas fault (Hill & Dibblee 1953). These findings, enhanced by subsequent studies, provided a basis for applying plate tectonic theory to the San Andreas fault system. Combined with the concept that right-lateral shear on the San Andreas system is related to the rifting of Baja California from North America (Wegener 1924, Hamilton 1961, Rusnak et al 1964), Wilson's (1965) proposal that the San Andreas fault is a continental transform quickly led to elaboration of the plate tectonic setting of the San Andreas fault and its role in the Pacific–North American boundary (Larson et al 1968, Moore & Buffington 1968, Atwater 1970, Larson 1972). The transform-fault paradigm gained support as it was tested and debated during the late 1960s and early 1970s (Dickinson & Grantz 1968; Hill 1971, 1974; Dickinson et al 1972; Huffman 1972; Kovach & Nur 1973; Baird et al 1974; Woodburne 1975; Campbell & Yerkes 1976; Matthews 1976).

This scientific colloquy led to additional studies in the late 1970s and, by the early 1980s, four areas of consensus had emerged. (*a*) The Gulf of California has opened 300 km since 4 to 5 Ma at a North American–Pacific plate rate of 5 to 6 cm/yr (Minster & Jordan 1978, Curray & Moore 1984). (*b*) Overall late Cenozoic displacement on the San Andreas fault in central California is ~300 km (Kovach & Nur 1973, Matthews 1976, Nilsen 1984, Ross 1984). (*c*) Late Cenozoic displacement on the San Andreas fault system in southern California is also ~300 km, but that displacement is distributed on three major faults, 240 km on the San Andreas and San Jacinto faults and 60 km on the San Gabriel fault (Crowell 1975, 1981; Ehlig 1981, 1982). (*d*) Late Cenozoic displacement on the San Andreas fault in northern California is ~450 km, which is the sum of displacements of 300 km on the San Andreas fault in central California and up to 150 km on the San Gregorio–Hosgri fault (Graham & Dickinson 1978, Clark et al 1984a).

By 1981, the plate-tectonic paradigm and the geologic history of the San Andreas fault had been integrated into a model that amalgamated the first three consensus items: ~300 km of offset across the San Andreas fault system, divided in southern California into ~240 km across the San Andreas fault proper and ~60 km across the San Gabriel fault, was equated to ~300 km of rifting in the Gulf of California since 5 Ma. Although this consensus transform-fault model incorporates much on-land and seafloor data, the model is inconsistent with other key data. Conflicting evidence is found in measurements of (*a*) overall displacement on faults of the San Andreas system in southern California, (*b*) slip rate on faults of the San Andreas system, and (*c*) plate-motion rate between North America and Baja California.

Some measurements of displacement on faults in southern California have proved to be irreconcilable with the widely cited consensus model. Thus, 1981 also saw the elucidation of an alternative model (Powell 1981), in which the San Andreas system has a much longer history than the 4 to 5 m.y. indicated by the consensus model. In this alternative model, ~100 km of right-lateral San Andreas displacement occurred during the early to middle Miocene on a fault that was subsequently disrupted by the San Gabriel fault and the San Andreas fault proper (Figure 3). Remnants of this early San Andreas fault include the Clemens Well, Fenner, and San Francisquito faults in southern California and the San Andreas fault in central and northern California. Displacement on the Clemens Well–Fenner–San Francisquito fault is about 1/3 of the overall displacement on the San Andreas system in southern California.

In the mid-1980s, other investigators documented a displacement of only 150 to 160 km on the San Andreas fault proper in southern California (Matti et al 1985, Frizzell et al 1986, Weldon 1986; see also Dillon 1975). Key evidence for this modest slip is a distinctive Triassic monzogranite that crops out in the San Bernardino Mountains east of the San Andreas fault and on Liebre Mountain west of the fault, but occurs northeast of the Clemens Well–Fenner–San Francisquito fault (Figures 3 and 4). The 150- to 160-km offset of this pluton on the San Andreas proper and the ~100-km displacement on the Clemens Well–Fenner–San Francisquito fault are mutually corroborating in that overall displacement on the San Andreas system as a whole is unchanged. Instead, displacement in southern California is redistributed in space and time within the system by subtracting ~100 km from the San Andreas fault proper and adding ~100 km to the older Clemens Well–Fenner–San Francisquito fault.

Holocene slip rates determined for the San Andreas fault in the 1980s led to further doubts about the consensus model. Sieh & Jahns (1984),

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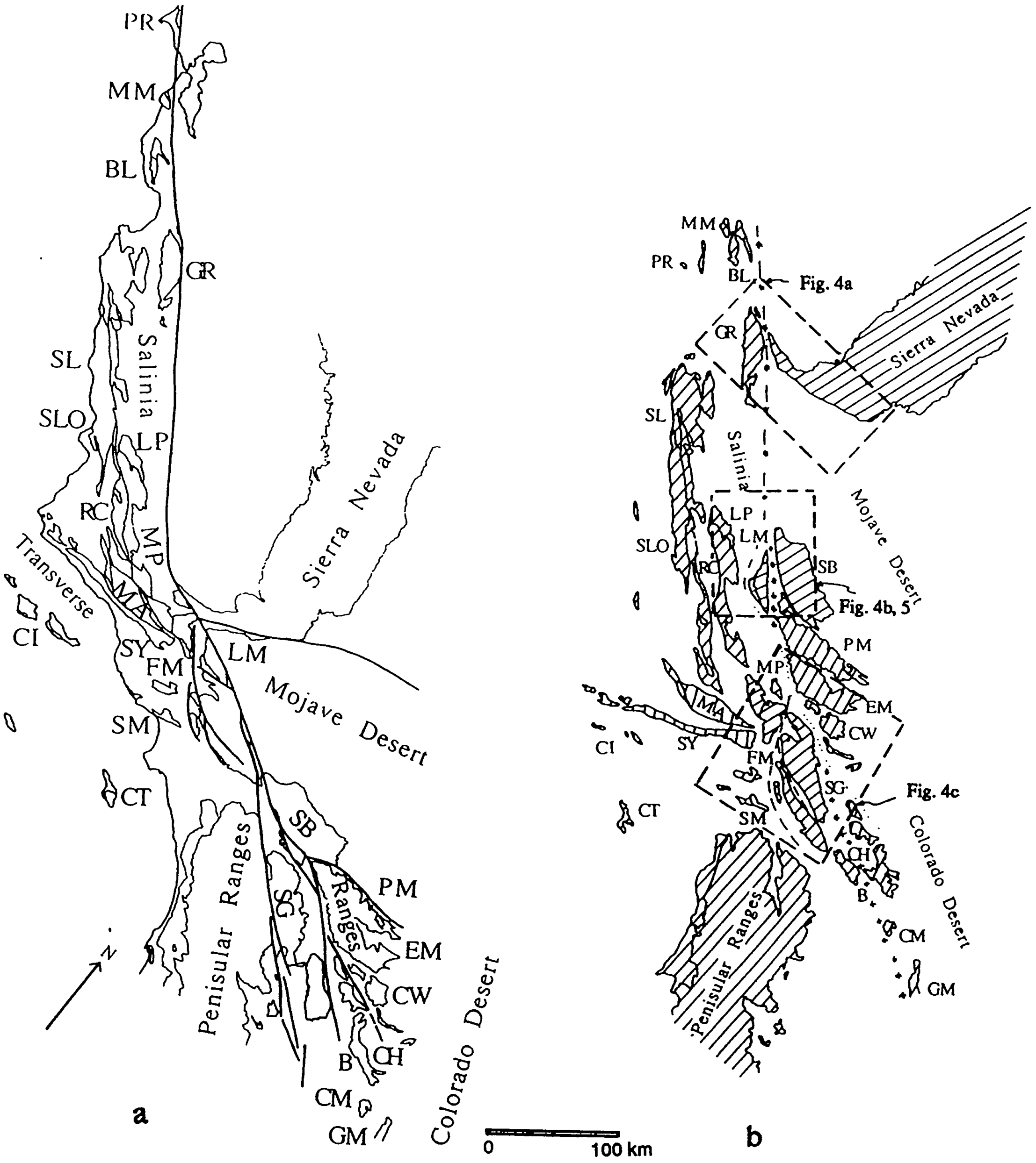
Figure 3 The San Andreas fault zone in California. (*a*) Index map showing the present-day distribution of rocks along the fault. B, Banning block; BL, Ben Lomond block; CH, Chocolate Mountains; CI, Channel Islands; CM, Cargo Muchacho Mountains; CT, Catalina Island; CW, Chuckwalla Mountains; EM, Eagle Mountains; FM, Frazier Mountain; GM, Gila Mountains; GR, Gabilan Range; LM, Liebre Mountain block; LP, La Panza Range; MA, Monte Arido block; MM, Montara Mountain; MP, Mount Pinos; PR, Point Reyes; RC, Rinconada block; SB, San Bernardino Mountains; SG, San Gabriel Mountains; SL, Santa Lucia Range; SLO, San Luis Obispo; SM, Santa Monica Mountains; SY, Santa Ynez Mountains. (*b*) The rocks reconstructed to their position prior to offset across the San Andreas system, ~20 to 22 Ma. Ruled lines show present north, to allow visualization of rotations. The future locations of various faults of the San Andreas system are shown with different symbols. See Powell (1992a) for details of the reconstruction and references for the rotations.



******	San Andreas fault
---------	San Gabriel fault
....	Clemens Well-Fenner-San Francisquito fault

Weldon & Sieh (1985), Perkins et al (1989), and Prentice et al (1991) demonstrated that the fault has slipped at 25 to 35 mm/yr during the Holocene, or about 1/2 to 2/3 the plate rate. Because slower rates have also been established for the San Andreas fault in southern California for the Pleistocene and the Pliocene (Weldon 1986, Weldon et al 1992), the San Andreas fault there would have required 7 to 10 m.y. rather than 4 or 5 m.y. to accumulate the ~240-km offset required by the consensus model. The discrepancy is compounded by the evidence that most of the slip on the San Gabriel fault—which in the model bears 60 of the 300 km of fault displacement that is linked to the opening of the Gulf of California since 4 or 5 Ma—actually occurred between 12 to 10 and 5 Ma (Crowell 1975, Crowell & Link 1982). The Quaternary and Pliocene slip-rate data indicate instead that the San Andreas fault has accumulated a displacement of ~150 km since about 5 Ma, an amount that complements the conclusions drawn from the measurements of overall displacement.

Further conflict between model and data arose when the calculated rate of slip between the Pacific and North American plates was reduced upon reexamination of the magnetic anomalies at the mouth of the Gulf of California (DeMets et al 1987, 1990; Ness et al 1991). The current best estimates range between 46 and 49 mm/yr, rather than the widely cited 56 mm/yr of Minster & Jordan (1978, 1984).

The evidence that the Quaternary and Pliocene slip rate on the San Andreas fault is significantly less than the relative plate motion rate led to discussion of a San Andreas "deficit" and to efforts to find the rest of the plate motion on other faults and to construct quantitative kinematic models for the plate boundary (Bird & Rosenstock 1984, Minster & Jordan 1984, Weldon & Humphreys 1986). Plate boundary deformation not only encompasses a broad zone along the San Andreas fault in the Coast Ranges, Transverse Ranges, Peninsular Ranges, and Salton trough, but also extends well east of the San Andreas in the Mojave Desert and the Basin and Range province and well west of the San Andreas in the western Transverse Ranges, southern Coast Ranges, and continental borderland [see papers and references in Crouch & Bachman (1984), U.S. Geological Survey (1987), Namson & Davis (1988a,b), Dokka & Travis (1990a,b), Lettis et al (1990), Rymer & Ellsworth (1990), Wallace (1990), and a forthcoming Geological Society of America Special Paper on the Seismotectonics of the central California Coast Range]. Structures attributed to shear along the plate boundary include right- and left-slip faults, reverse and normal faults, contractional folds at the surface, and inferred decollements at depth.

In the last five years, space-based geodesy has provided measurements of site-movement along faults of the San Andreas fault system, yielding a present-day plate motion rate of 45 to 50 mm/yr and present-day slip rates that are mostly the same as the Quaternary slip rates (Kroger et al 1987, Ward 1990). These present-day slip rates largely corroborate kinematic models that require the San Andreas fault, as only one fault within a broad, complex plate boundary, to slip at a slower rate than the 60 mm/yr required by the consensus model.

KEY EVIDENCE FOR A NEW MODEL

Displacement on the San Andreas and related late Cenozoic faults is a passive response to the gravitational and thermal driving mechanisms for the fault system. Thus, our understanding of the geologic evolution of the San Andreas fault system depends on our knowledge of displacement and timing of movement on each of the faults in the system and on the kinematic relations among the various faults. Recent efforts to understand the San Andreas system as a whole have emphasized the need to balance the strain budget for the system (Bird & Rosenstock 1984; Weldon & Humphreys 1986; Humphreys & Weldon 1991, 1992) and to maintain mass balance in restoring slip on the system (Powell 1992a). An important consequence of these studies is the recognition that slip rate and displacement measured on the San Andreas fault proper vary along its length depending on the deformation accommodated both in space and time by other faults of the system.

Recent study of the San Andreas fault system has progressed in five complementary ways, leading to reassessment of the magnitude and timing of displacement on various faults of the system. (*a*) Overall displacement has been more completely constrained by reconstruction of paleogeologic domains that existed prior to inception of the fault system. (*b*) Additional incremental displacements have been established by measuring offsets of rocks and structures that formed during the growth of the fault system. (*c*) Timing of fault movement has been further constrained by documenting the ages both of the youngest rocks that are fully displaced and of rocks that have been incrementally displaced. (*d*) The sequence of fault movement has been newly established both by the steps necessary to reconstruct pre–San Andreas paleogeologic domains and by the age of rocks and structures that formed coevally with the fault system. (*e*) Slip rates have been calculated from geologic, geodetic, and seismic measurements of strain.

Magnitude and Timing of Overall Displacements

The regional paleogeologic framework of southern and central California constrains overall reconstruction of rocks along the San Andreas fault system [for additional discussion and references, see Powell (1992a); see also Crowell (1962), Woodburne (1975), Ross (1984), and papers in Crowell (1975), Howell & McDougall (1978), Ernst (1981, 1988), Ingersoll & Woodburne (1982), Ingersoll & Ernst (1987), and Powell et al (1992)]. The oldest part of this framework comprises a northwest-trending belt of cratonic Early and Middle Proterozoic plutonic and metamorphic rocks overlain by metamorphosed Late Proterozoic and Paleozoic strata. This belt is flanked by belts of metamorphosed Mesozoic volcanic and sedimentary rocks, and all the belts were intruded by distinctive suites of Mesozoic plutonic rocks. Fault-bounded terranes were delimited during the late Mesozoic and early Cenozoic: the Pelona, Orocopia, and Rand Schists and related rocks were thrust beneath the cratonic-batholithic terrane; the Franciscan Complex and the Catalina Schist were juxtaposed tectonically outboard of the cratonic-batholithic terrane, and the Coast Range ophiolite and depositionally overlying Upper Jurassic to Lower Cretaceous strata of the lower part of the Great Valley sequence were faulted above the Franciscan-Catalina terrane and, in the southern Coast Ranges and Western Transverse Ranges, against the cratonic-batholithic terrane. Upper Cretaceous through Eocene marine strata crop out along the boundary between the cratonic-batholithic and Franciscan-Catalina terranes in the Coast Ranges, western Transverse Ranges, and Peninsular Ranges. These strata include both those that constitute the upper part of the Great Valley sequence and overlying units and those that depositionally overlap the western margin of the cratonic-batholithic terrane. Along with the Coast Range ophiolite and lower part of the Great Valley sequence, these strata are superposed tectonically over the eastern margin of the Franciscan-Catalina terrane. The Pelona–Orocopia–Rand and Franciscan-Catalina terranes are exposed in antiforms that breach the tectonically superjacent terranes. Upper Oligocene and lower Miocene terrestrial and marine sedimentary and volcanic strata filled basins that formed in the cartonic-batholithic and Coast Range ophiolite–Great Valley terranes and in Upper Cretaceous–Eocene rocks; in the Transverse Ranges and southern Coast Ranges, the Oligocene and Miocene strata were faulted against the Pelona-Orocopia and Franciscan-Catalina terranes along extensional faults associated with the uplift of these metamorphic terranes.

Within the general pattern of these regional paleogeologic terranes, Powell (1992a) has defined four paleogeologic reference domains which consist of specific combinations of rocks and structures from the regional terranes. Three of these reassembled reference domains are shown in Figure 4. The northernmost domain comprises metamorphosed upper Paleozoic or lower Mesozoic strata, Mesozoic gabbroic and granitic plutonic rocks, Pelona Schist and related rocks, Eocene marine strata, and upper Oligocene terrestrial and marine sedimentary and volcanic rocks currently found in the Gabilan Range and vicinity west of the San Andreas fault and in the San Emigdio and Tehachapi Mountains and on Portal Ridge and vicinity east of the San Andreas (Figure 4*a*). This domain is based on well established correlations across the central reach of the San Andreas fault between the Transverse Ranges and San Francisco Bay (Ross 1984; see also Kovach & Nur 1973, Nilsen 1984) and has been displaced by ~295 km along the San Andreas. The youngest rocks in this domain that are displaced ~295 km by the San Andreas fault are the 22- to 24-m.y.-old Pinnacles and Neenach Volcanics (Kovach & Nur 1973, Matthews 1976, Sims 1992).

A second paleogeologic reference domain contains metamorphosed Proterozoic or lower Paleozoic strata, Mesozoic plutonic rocks, and Upper Cretaceous through Eocene marine strata now found in the La Panza Range and Liebre Mountain block west of the San Andreas fault proper and in the San Bernardino Mountains east of the San Andreas (Figure 4*b*). This domain is based in part on recent lithologic correlations (Joseph et al 1982, Frizzell et al 1986) and its reconstruction requires restoring a displacement of 150 to 160 km on the San Andreas fault (Matti et al 1985, Frizzell et al 1986, Matti & Morton 1992, Powell 1992a, Weldon et al 1992) and a combined displacement of 140 to 150 km on the Clemens Well–Fenner–San Francisquito–San Andreas and San Gabriel faults.

A third paleogeologic reference domain consists of Proterozoic gneiss units, Mesozoic plutonic rocks, Eocene marine strata, and upper Oligocene and lower Miocene terrestrial strata currently found west of the San Andreas and San Gabriel faults on Frazier Mountain, Mount Pinos, and in the vicinity; east of the San Andreas and Clemens Well faults in the eastern Orocopia and Chuckwalla Mountains and the vicinity; and between the San Andreas and San Gabriel faults and south of the San Francisquito fault in the Sierra Pelona, Soledad basin, and northern San Gabriel Mountains (Figure 4*c*). Reconstruction of this domain requires a combined displacement of about 305 to 315 km on the Clemens Well–Fenner–San Francisquito, San Gabriel, and San Andreas faults (Powell 1992a). The youngest rocks in this domain that are displaced 305 to 315 km by the San Andreas fault system are: the 20- to 26-m.y.-old volcanic strata (Frizzell & Weigand 1992) of the Plush Ranch Formation of Carman (1964), the Diligencia Formation of Crowell (1975), and the Vasquez Formation; and the ca. 20- to 22-Ma Arikareean(-Hemingfordian?) strata (Woodburne 1975) of the Diligencia Formation and the Tick Canyon Formation of Jahns (1940).

Reconstruction of this third reference domain provides four important constraints on the evolution of the San Andreas fault system (summarized from Powell 1992a). First, it requires that the Clemens Well, Fenner, and

EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

☐ Holocene to middle Miocene strata

▩ Early Miocene and Oligocene sedimentary rocks—Includes Plush Ranch (PR), Tick Canyon (TC), Vasquez (V), and Diligencia (D) Formations in Figure 4c

▩ Early Miocene and Oligocene volcanic rocks—Includes Vasquez Formation (V) in Figure 4c, Pinnacles (PV) and Neenach (NV) Volcanics in Figure 4a

▩ Eocene sedimentary rocks

▩ Paleocene sedimentary rocks

▩ Late Cretaceous sedimentary rocks

PLUTONIC AND METAMORPHIC ROCKS

▨ Cretaceous quartz dioritic rocks

▨ Cretaceous gneissic quartz dioritic rocks and Early Cretaceous and older gneiss

☐ Cretaceous and Jurassic granitic rocks, undivided

▤ Cretaceous or Jurassic very coarse-grained monzogranite

▤ Pelona and Orocopia Schists and schist of Sierra de Salinas, undivided

■ Jurassic and Triassic(?) gabbro and diorite—Jurassic rocks shown in Figure 4a; Triassic(?) rocks shown in Figure 4c

▦ Jurassic to Triassic and late Paleozoic(?) carbonate rocks and schist and quartzite

▦ Triassic monzodioritic rocks—Includes Mount Lowe igneous pluton of Barth & Ehlig (1988)

▦ Paleozoic miogeoclinal strata

■ Mesozoic and Paleozoic, or Proterozoic metasedimentary and metaigneous suites of Limerock Canyon

▩ Middle Proterozoic anorthosite-syenite complex

▩ Early Proterozoic augen gneiss of Monument Mountain of Powell (1991a)

▩ Early Proterozoic metasedimentary rocks, amphibolite, and laminated granitic orthogneiss—As mapped, also includes Middle Proterozoic gneiss

▨ Early Proterozoic granitic augen gneiss and overlying Early or Middle Proterozoic metasedimentary rocks

* * * * * San Andreas fault

□ □ □ □ □ Punchbowl fault

— — — San Gabriel fault

○ ○ ○ ○ ○ Clemens Well-Fenner-San Francisquito fault

Figure 4 Detailed reconstructions of key reference domains along the San Andreas fault. After Powell (1992a). (*a*) Gabilan Range–San Emigdio Mountains–Portal Ridge paleogeologic reference domain reassembled by restoring right slip of 295 km on the San Andreas fault proper and left slip of 12 km on the western segment of the Garlock fault. NV, Neenach Volcanics; PV, Pinnacles Volcanics. (*b*) La Panza Range–Liebre Mountain–San Bernardino paleogeologic reference domain reassembled by restoring right slip of 162 km on the San Andreas fault proper, including 42 km on the Punchbowl fault strand; 42 km on the San Gabriel–San Andreas fault; and 110 km on the Clemens Well–Fenner–San Francisquito–San Andreas fault.

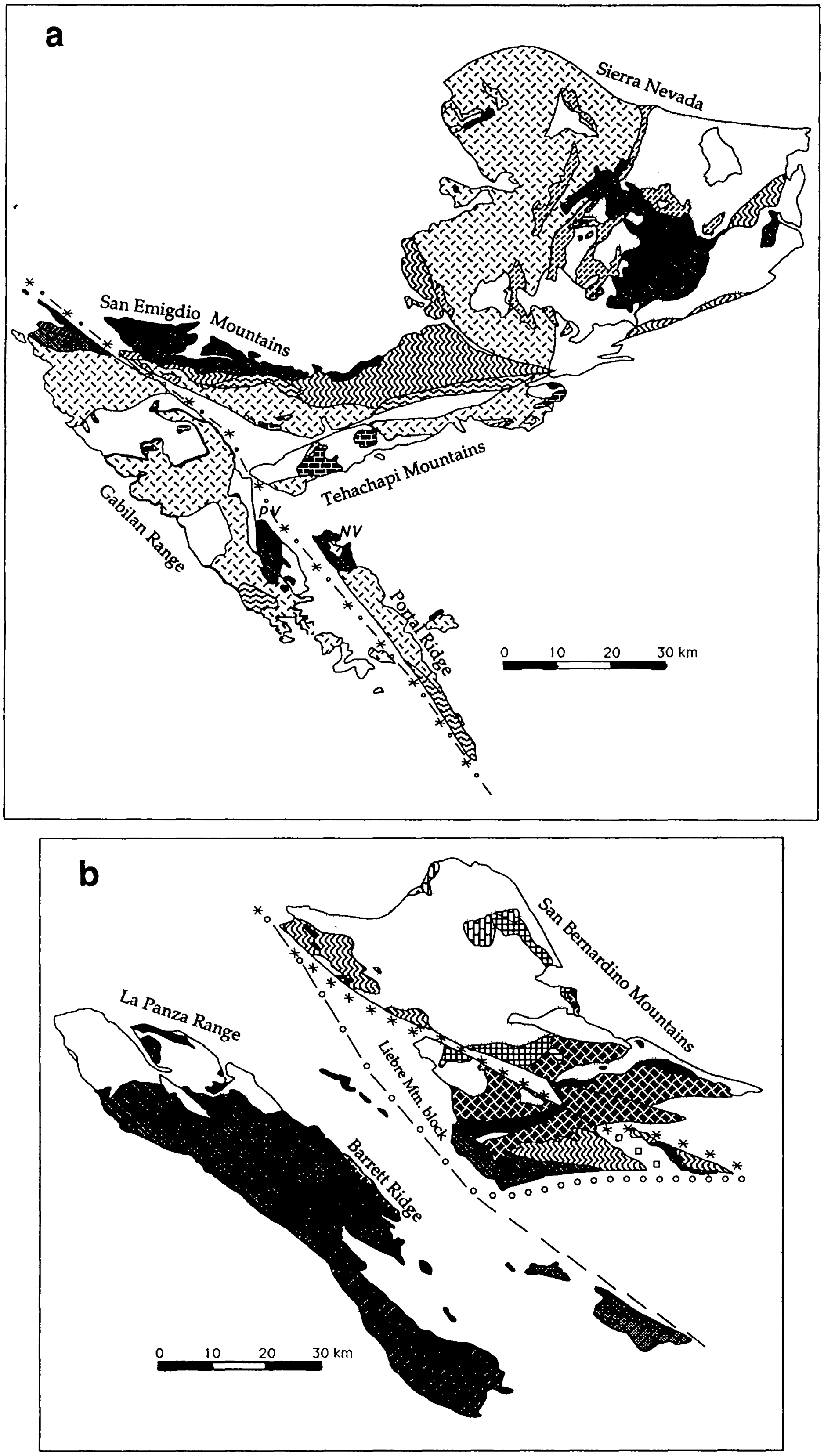


Figure 4—continued

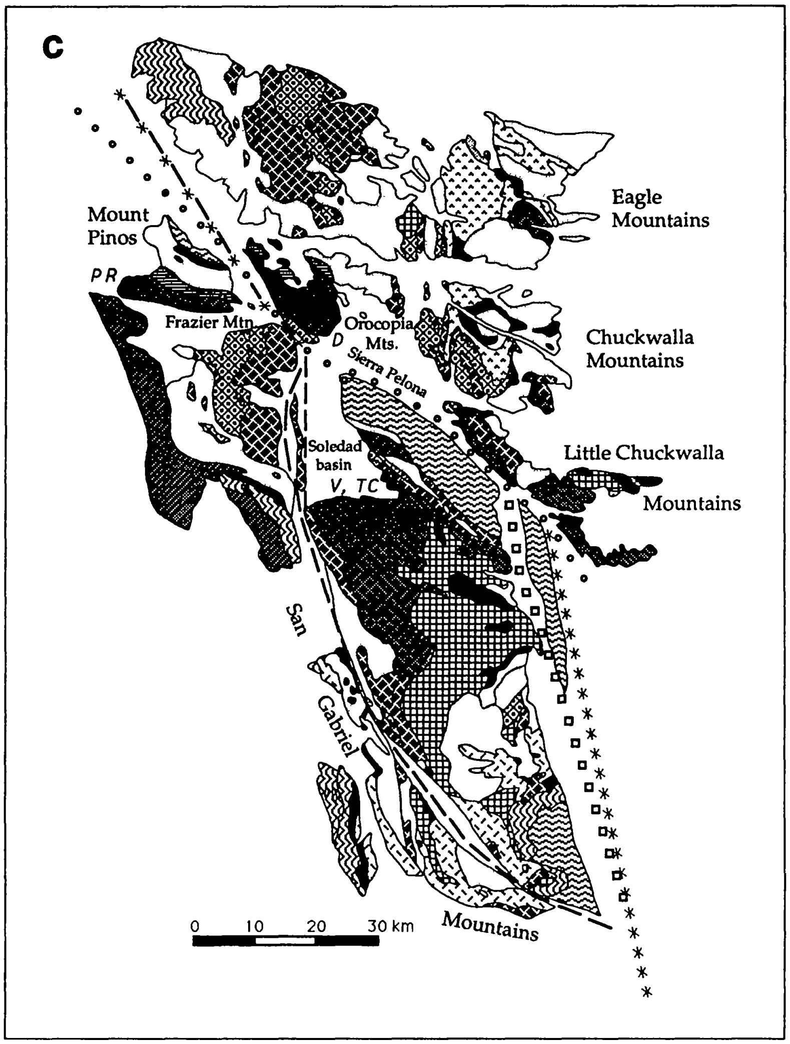


Figure 4c Frazier Mountain–eastern Orocopia Mountains–Soledad basin paleogeologic reference domain reassembled by sequentially restoring left slip of 8 and 11 km on the Salton Creek and Chiriaco faults, respectively, and right slip of 162 km on the San Andreas fault proper, 42 km on the San Gabriel–San Andreas fault, and 110 km on the Clemens Well–Fenner–San Francisquito–San Andreas fault. D, Diligencia Formation of Crowell (1975); PR, Plush Ranch Formation of Carman (1964); TC, Tick Canyon Formation of Jahns (1940); V, Vasquez Formation.

San Francisquito faults were parts of a single, throughgoing strike-slip fault. Second, it indicates that the combined overall displacement on the Clemens Well–Fenner–San Francisquito, San Gabriel, San Andreas, and San Jacinto faults of the San Andreas fault system in southern California is 305 to 315 km. Third, in order to effect the reconstruction, displacement must be restored sequentially, first on the San Jacinto fault and the San Andreas fault proper, then on the San Gabriel fault, and finally on the Clemens Well–Fenner–San Francisquito fault: Any other sequence will not result in the proper reassembly of the rocks of the paleogeologic reference domain. Fourth, in order to allow the Frazier Mountain-Mount Pinos block to be rejuxtaposed against the eastern Orocopia Mountains by restoring slip on the Clemens Well–Fenner–San Francisquito fault, the Frazier Mountain-Mount Pinos block can be restored no more than 42 to 45 km on the San Gabriel fault. Thus, if displacement on the San Andreas fault proper in southern California is ~160 km, then displacement on the Clemens Well–Fenner–San Francisquito fault is about 100 to 110 km.

Simultaneous reconstruction of all the reference domains provides additional constraints (summarized from Powell 1992a). First, while it was active, the Clemens Well–Fenner–San Francisquito fault must have extended northward along the central reach of the San Andreas fault. In other words, during the late early and early middle Miocene, the Clemens Well–Fenner–San Francisquito fault *was* the San Andreas fault in southern California and the Clemens Well–Fenner–San Francisquito–San Andreas fault was the only throughgoing right-lateral strike-slip fault in California. Second, a balanced reconstruction can only be achieved by also restoring displacements on strike-slip faults that were active after about 5 Ma: (*a*) right slip of 24 to 28 km documented on the San Jacinto fault (Sharp 1967, Bartholomew 1970); (*b*) cumulative right slip of 30 to 40 km documented on the northwest-striking faults of the central Mojave Desert (Dokka 1983, Dokka & Travis 1990a, who postulated an additional 40 km of right slip on faults in the eastern Mojave desert); (*c*) left slip of ~12 km postulated for the western segment of the Garlock fault (Powell 1992a), presumably increasing eastward to 56 to 64 km along the central reach of the fault (Smith 1962, Davis & Burchfiel 1973); (*d*) cumulative left slip of 45 to 50 km documented on the east-striking faults of the Transverse Ranges east of the San Andreas fault; and (*e*) as much as ~10 km of left slip on the northeast-trending faults in the southeastern San Gabriel Mountains. If real, the discrepancy in displacement on the western and central parts of the Garlock fault is unresolved. Third, no more than 23 km of displacement on the San Gabriel fault can rejoin the San Andreas fault proper to the southeast and connect with the Salton trough–Gulf of California region (compare Matti & Morton 1992, Weldon et al 1992).

In order to complete a balanced reconstruction of the San Andreas fault system Powell (1992a) suggested that the measured overall displacement of 45 km on the Rinconcada–Reliz fault (Graham 1978) merged northward with the San Gregorio–Hosgri fault, which exhibits an overall displacement of 105 km south of the junction (Nagel & Mullins 1983) and 150 km north of the junction (Clark et al 1984a).

Because paleogeologic patterns in Proterozoic through late Cenozoic rocks in the cratonic-batholithic terrane of southern and central California are fully reassembled by restoration of slip along the faults of the San Andreas system, the balanced reconstruction invalidates displacements that are significantly larger than those used in making the reconstruction (Powell 1992a,b). This restriction applies not only to larger measurements based on cross-fault stratigraphic or lithologic correlations for the faults of the San Andreas system (Ross et al 1973, Graham et al 1989), but also to large displacement postulated on any hypothetical pre-, proto-, or syn-San Andreas faults. Such faults have been postulated to account for perceived differences in overall displacement on the San Andreas north of, versus in and south of, the Transverse Ranges, to accommodate unreconciled plate motion, and to provide a docking structure for rocks that have yielded anomalously low paleomagnetic inclination data (Suppe 1970, Anderson 1971, Dickinson et al 1972, Garfunkel 1973, Beck 1986, Sedlock & Hamilton 1991).

Movement on the Clemens Well–Fenner–San Francisquito–San Andreas fault is bracketed between 20 to 17 and 13 to 12 Ma (Powell 1992a). The older age limit is based on the inferred full displacement of Saucesian (lower Miocene) strata along the central reach of the San Andreas fault (Stanley 1987b), on stratigraphic and sedimentologic evidence in upper Saucesian strata of the Temblor Formation east of the San Andreas fault for a northwest-moving source to the west (O'Day & Sims 1986), and on full displacement of 20- to 26-m.y.-old volcanic rocks and 20- to 22-m.y.-old Arikareean(-Hemingfordian?) (lower lower Miocene) strata in southern California and of 22- to 24-m.y.-old volcanic rocks in central California. The younger age limit is based on the overlap of the Fenner fault by the lower Clarendonian (upper middle Miocene) basal strata of the Punchbowl Formation (Woodburne 1975) and on the overlap of the San Francisquito fault by the Barstovian (middle Miocene) San Francisquito Canyon breccia unit of Sams (1964, Szatai 1961) and the upper Clarendonian (lower upper Miocene) upper part of the Mint Canyon Formation (Woodburne 1975). Based on magnetostratigraphic data, the base of the Punchbowl Formation was deposited at 13 Ma (Liu 1990). Furthermore, clasts in the upper Barstovian lower part of the Mint Canyon Formation that were derived from the north include Pelona Schist from south of the San Francisquito fault and Paleogene marine sandstone from north of the fault (Ehlert 1982), indicating that most movement on the fault was over by the late Barstovian. Evidence for dextral shear in the vicinity of the San Andreas fault between 22 and 26 Ma (Graham et al 1989, Yeats et al 1989) indicates that dextral shear predated the existence of a throughgoing strike-slip fault.

Most of the movement on the San Gabriel, San Gregorio–Hosgri, and Rinconada–Reliz faults occurred between 13 to 11 and 5 Ma (Powell 1992a). The older age limit of 13 to 11 Ma for the San Gabriel fault is indicated by the full displacement of the lower part of the Mint Canyon

Formation, which is late Barstovian to possibly early Clarendonian in age (Woodburne 1975), and the lower two members of the Caliente Formation in Lockwood Valley and the Dry Canyon area of the Cuyama badlands, which range in age from Hemingfordian through early Clarendonian (early and middle Miocene) (Carman 1964, Woodburne 1975). On the basis of fossil and magnetostratigraphic evidence, movement on the San Gabriel fault associated with deposition of the Violin Breccia occurred between about 10 and 6 or 5 Ma (Crowell & Link 1982). After deposition of the Violin Breccia, 1 to 2 km of displacement has occurred on the San Gabriel fault since 3 or 4 Ma. Locally, the San Gabriel fault has been active during the Quaternary (Cotton 1986, Weber 1986). The San Gregorio–Hosgri fault began moving after 13 to 12 Ma and prior to 11 Ma, had accumulated 80 km of displacement by 6 or 7 Ma, and has slipped an additional 70 km since then (Clark et al 1984a). The San Gregorio–Hosgri fault has been active in the Quaternary (Silver & Normark 1978, Weber & Cotton 1981, Hanson & Lettis 1990).

The youngest units that are inferred to have been displaced 150 to 170 km or more on the San Andreas fault include the upper Miocene and Pliocene Imperial Formation in San Gorgonio Pass from the upper Miocene and Pliocene Bouse Formation in the southern Chocolate Mountains and subsurface upper Miocene strata in the Yuma basin (Dillon 1975, Dillon & Ehlig 1992), and the Pliocene Hungry Valley Formation in the Ridge Basin from a crystalline-rock source terrane in the San Bernardino Mountains (Crowell & Link 1982, Matti et al 1985, Frizzell et al 1986, Weldon et al 1992). All of these formations include rocks at least as young as 5 or 6 Ma, indicating that little dextral movement occurred on the Mojave Desert and Salton trough segments of the San Andreas fault prior to about 5 Ma.

During the time the San Andreas fault has been active, most of the deposits which formed along it have been terrigenous sediments, typically limited to small basins. Recently, substantial progress has been made in southern California in characterizing and dating sediments of this type that range in age from late Miocene through Quaternary. For example, there has been the recent recognition and dating of several pull-apart basins along the San Andreas fault that predate the modern San Andreas fault; these include the Mill Creek basin (Sadler et al 1992) and the Devil's Punchbowl (Weldon 1986, Weldon et al 1992). The existence of these basins provides evidence for incipient dextral shear near part of the trace of the modern San Andreas fault prior to 5 Ma and perhaps as early as 13 Ma—that is, during the time that the San Gabriel fault was active.

However, paleogeographic and paleostructural evidence indicates that essentially all of the 150 to 160 km of movement on the Mojave Desert segment of the San Andreas proper in southern California has occurred since about 5 Ma. The Ridge and Santa Ana basins have been displaced ~150 km from their source terranes. The proto–San Bernardino Mountains, which were uplifted on the Squaw Peak thrust from about 10 to 5 Ma, provided the right provenance for most of the sediments deposited in the Ridge basin (south-directed sediment path, Figure 5) (Weldon 1986, Meisling & Weldon 1989, Weldon et al 1992). Moreover, distinctive clasts in sediments in the Santa Ana basin in the San Bernardino Mountains may have been derived from the proto–San Gabriel Mountains (north-directed sediment path, Figure 5) at this time (10 to 5 Ma); alternatively, the clasts may have been shed northeast, orthogonal to the San Andreas since about 5 Ma after the San Andreas had accumulated some offset (Sadler 1992). The Liebre Mountain thrust, which developed as part of the Squaw Peak thrust between 10 and 5 Ma, has since been displaced ~150 km from the Squaw Peak thrust along the San Andreas fault (Weldon 1986, Meisling & Weldon 1989, Weldon et al 1992). The San Gabriel and Cajon Valley faults, which may have been a single fault until about 5 Ma, are now separated by ~150 km along the San Andreas fault (Matti et al 1985, Weldon 1986, Matti & Morton 1992, Weldon et al 1992).

Average Slip Rates

Long-term average slip rates for various faults of the San Andreas system have been calculated from geologic evidence for magnitude and timing of displacement [for additional discussion and references, see Clark et al (1984b), Wesnousky (1986), Brown (1990), and the U.S. Geological Survey (1990)]. Incremental Holocene displacement has been measured at many localities, Pleistocene displacement at a few. Variously well-constrained calculations have yielded different Holocene average dextral slip rates for the various segments of the San Andreas fault proper: between 23 and 35 mm/yr on the Salton trough segment of the San Andreas (Keller et al 1982, Sieh 1986); ~25 mm/yr on the segment of the San Andreas between San Gorgonio and Cajon Passes (Weldon & Sieh 1985, Weldon 1986, Harden & Matti 1989); ~35 mm/yr on the section of the San Andreas bounding the Mojave Desert and Carrizo Plain (Sieh & Jahns 1984, Salyards 1989); between 20 and 25 mm/yr near San Juan Bautista (Perkins et al 1989); at least 9 mm/yr near San Francisco (Brown 1990, Prentice et al 1991); and between 20 and 25 mm/yr north of San Francisco (Prentice et al 1991). Incremental offsets of Pleistocene fanglomerate units have been shown by linking distinctive suites of clasts in fanglomerate units in the Mojave Desert east of the fault to source areas in the San Gabriel Mountains west of the fault that are tapped by major drainages debouching onto the Mojave Desert (Weldon 1986, Weldon et al 1992). These offsets yield a

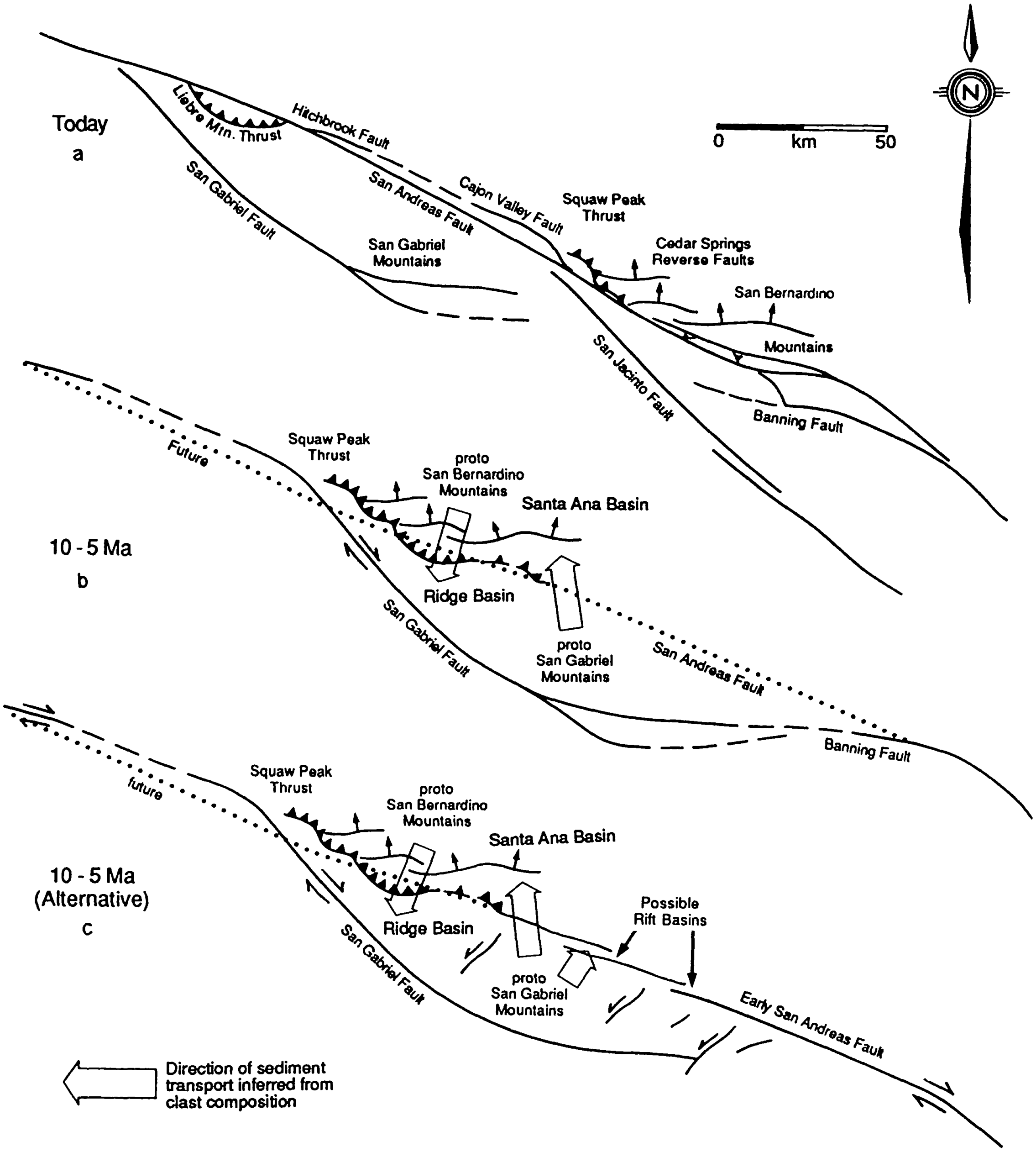


Figure 5 Reconstruction of late Miocene paleogeologic features along the modern San Andreas fault. After Weldon (1986) and Meisling & Weldon (1989). The correlation of rocks, structures, paleogeographic features, and sediment provenance indicates an offset of ~150 km since 5 Ma. Large arrows show direction of sediment transport inferred from clast assemblages. (*a*) Present-day distribution of late Miocene faults and sedimentary basins along the San Andreas fault in the central Transverse Ranges. (*b*) Preferred reconstruction of Squaw Peak–Liebre Mountain thrust fault and late Miocene paleogeography along the San Andreas fault. The San Gabriel fault and Squaw Peak–Liebre Mountain thrust are active. (*c*) Alternative reconstruction of late Miocene faults and paleogeography. The San Gabriel fault, Squaw Peak–Liebre Mountain thrust, and the southern part of the San Andreas fault are active, with pull-apart rift basins developing along the San Andreas.

Pleistocene slip rate of 35 mm/yr for the Mojave Desert segment of the San Andreas fault. Collectively, these data clearly indicate that the rate of slip on the San Andreas proper during the Quaternary has been about 1/2 to 3/4 the Pacific–North American plate rate since 4 or 5 Ma, which is currently calculated to be in the range of 46 to 48 mm/yr from the Gulf of California northward through California (DeMets et al 1987, 1990; Kroger et al 1987; Ward 1990).

The deficit in movement along the plate boundary and the differences in strain rate on the various segments along the San Andreas are approximately balanced by slip rates measured on other structures [for additional discussion and references, see Weldon & Humphreys (1986); Wesnousky (1986); Brown (1990); U.S. Geological Survey (1990); and Humphreys & Weldon (1991, 1992)]. Part of the strain deficit is accommodated on strike-slip faults that intersect the San Andreas fault, including 8 to 17 mm/yr for the right-lateral San Jacinto fault (Sharp 1981, Morton & Matti 1992), 2 to 3 mm/yr for the western reach of the Garlock fault (Clark et al 1984b), 7 mm/yr for the central reach of the Garlock fault during the Holocene and probably since the latest Miocene (Carter 1987), 4 to 12 mm/yr for the right-lateral Calaveras and Hayward faults (Lienkaemper et al 1991), and 5 to 11 mm/yr during the Pleistocene for the right lateral San Gregorio–Hosgri fault (Weber & Cotton 1981, Weber 1983, Hanson & Lettis 1990).

Strain is also accommodated by right-lateral faults that do not intersect the San Andreas, including faults in the north-central Mojave Desert, across which an overall slip rate of 7 mm/yr has been calculated from geodetic measurements (Sauber et al 1986), and the Elsinore fault, for which slip rates in the range 3 to 9 mm/yr have been calculated (Lamar & Rockwell 1986). In addition, Quaternary rates of convergence in the Transverse Ranges range from less than 1 to 6 mm/yr on reverse faults along the south flank of the San Gabriel Mountains (Clark et al 1984b) to 17 to 23 mm/yr distributed chiefly on various reverse faults and contractional folds along the flanks of the Ventura basin, with as much as 10 mm/yr on individual structures (Yeats 1983, U.S. Geological Survey 1987, Rockwell 1988).

In general, average Holocene slip rates for the San Andreas fault system calculated from geologic data agree with modern slip rates calculated from trilateration networks, very long baseline interferometry (VLBI) experiments, and seismic moments [for further discussion and references, see Wesnousky (1986), Kroger et al (1987), Wallace (1990), Ward (1990), and Lisowski et al (1991)].

To date, details about the magnitude and timing of incremental Pliocene displacement on the San Andreas have been inferred only along the Mojave Desert segment (see Weldon et al 1992) where the magnetostratigraphically dated Phelan Peak Formation of Weldon et al (1992) received sediment across the fault from successively more southeastward sources as it was deposited northeast of the San Andreas. These incremental offsets yield a Pliocene slip rate on the San Andreas of 30 to 40 mm/yr—essentially equal to that of the Quaternary (Weldon et al 1992). Other recent calculations yield roughly a 30–40 mm/yr range of Pliocene slip rates in central and northern California—essentially equal to that of the Quaternary rates on the San Andreas in central California and on the San Andreas and Calaveras-Hayward faults in northern California (Fox et al 1985, Sims 1992). Thus, the rate of slip on the San Andreas proper during the Pliocene is also significantly less than the Pacific–North American plate rate, with the deficit balanced by dextral shear distributed over other faults in the system (Weldon & Humphreys 1986).

Uncertainties about the ages of units older than 5 Ma lead to still less well constrained long-term average slip rates for older faults of the San Andreas system. For a displacement of ~45 km in the interval between 12 ± 1 and 5 ± 1 Ma, the range of possible slip rates is 5 to 9 mm/yr for the San Gabriel fault (Powell 1992a) and for the San Andreas fault north of its intersection with the San Gabriel fault (Powell 1992a, Sims 1992). This range of possible rates is 2/5 to 3/4 the rate of 12 mm/yr that can be calculated for a displacement of 60 km accumulating between about 10 and 5 Ma (age range of the Violin Breccia). For a displacement of 100 to 110 km, the range of possible slip rates is 12 to 28 mm/yr for the Clemens Well–Fenner–San Francisquito–San Andreas fault if it was active between 20 to 17 and 13 to 12 Ma (see Powell 1992a).

Time-Displacement History

The history of the San Andreas fault system can be summarized by an offset vs age curve [Figure 6; compare and contrast Hill (1971), Dickinson et al (1972), Graham et al (1989), Sedlock & Hamilton (1991)], from which we draw three conclusions about the time-displacement history of the San Andreas fault. First, the magnitude and timing of movement on the Clemens Well–Fenner–San Francisquito, San Gabriel, San Andreas proper, and San Jacinto faults in and south of the Transverse Ranges are equivalent to the magnitude and timing of movement on the San Andreas fault proper between the Transverse Ranges and San Francisco. Second, there are distinct phases in the time-displacement evolution of the San Andreas fault system: (*a*) ~35 mm/yr since 4 to 5 Ma on the San Andreas fault proper—including the San Jacinto fault south of its junction with the San Andreas and the Calaveras–Hayward fault north of its junction with the San Andreas, (*b*) ~5 to 10 mm/yr between 13 to 11 and 6 to 4 Ma on the San Gabriel–San Andreas fault, and (*c*) ~10 to 30 mm/yr between 20 to 17 and 13 to 12 Ma on the Clemens Well–Fenner–San

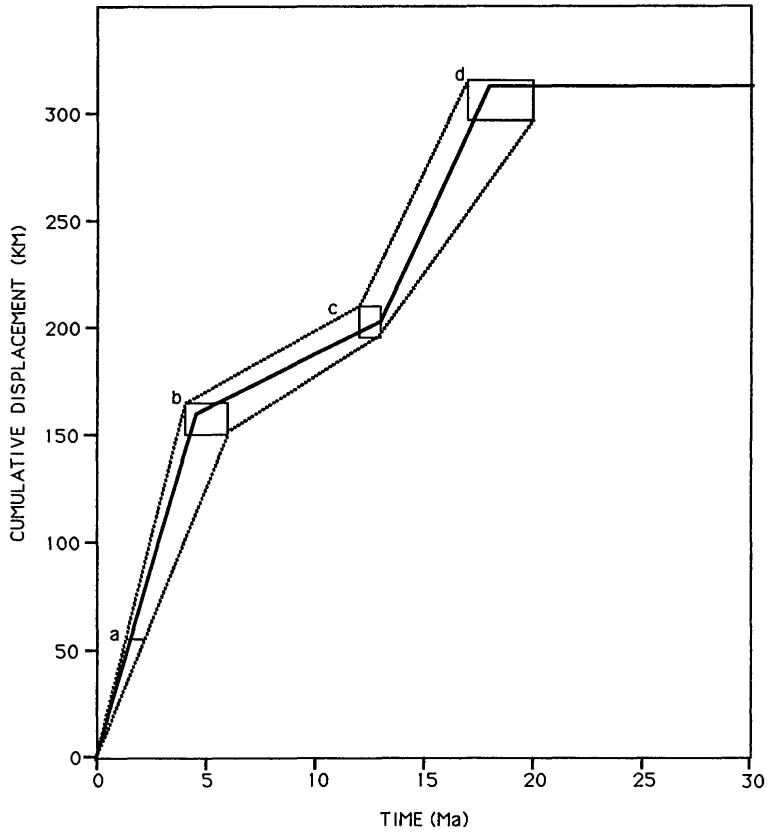


Figure 6 Displacement vs time curve for the San Andreas, San Gabriel, and Clemens Well–Fenner–San Francisquito faults of the San Andreas system. Box *a* is based on a continuous, dated record of offset spanning the Pleistocene, which demonstrates a constant rate of ~35 mm/yr on the San Andreas fault north of the San Gabriel Mountains (Weldon 1986, Weldon et al 1992). Boxes *b* to *d* represent the stratigraphic and structural constraints on magnitude and timing of inception and cessation of successive phases of the fault system, as summarized above. The boxes and curve also incorporate the premises that slip on the San Andreas system was continuous from one phase to next and that slip was transferred completely between phases. The solid curve represents a three-phase history of slip, with 22 mm/yr for the Clemens Well–Fenner–San Francisquito–San Andreas fault between 18 and 13 Ma, 5 mm/yr for the San Gabriel–San Andreas fault between 13 and 5 Ma, and 35 mm/yr for the San Andreas proper since 5 Ma. The uncertainties, however, generate envelopes of possible time-displacement curves.

Francisquito–San Andreas fault. Third, we find no evidence for a gradual or continuous increase in rate with time as hypothesized by early workers (for example, Dickinson et al 1972). The rate increased around 4 to 5 Ma and has changed little.

EVOLVING ROLE IN THE PLATE BOUNDARY

Interaction between the North American and Pacific plates began about 29 Ma when the East Pacific Rise intersected the subduction zone between the Farallon and North American plates at the Pioneer and Mendocino fracture zones (Atwater 1970, 1989). Dextral relative motion between the two plates led to the growth of a transform-fault boundary along which the San Andreas fault formed (Wilson 1965; McKenzie & Morgan 1969; Atwater 1970, 1989; Dickinson & Snyder 1979; Dickinson 1981; Irwin 1990). According to the theoretical geometrical model for transform growth, the transform-ridge-trench triple point that resulted from the intersection of the Mendocino fracture zone and Farallon–North American trench "instantaneously" evolved into a transform-transform-trench triple point and a transform-ridge-trench triple point that migrated apart along a continental-margin transform fault. Currently, however, these plate-boundary triple junctions, located near Cape Mendocino and the mouth of the Gulf of California, are linked by the San Andreas fault and a set of transforms in the gulf, well inland from the expected position along the continental margin.

Most of the models proposed for the plate tectonic evolution of the San Andreas system oversimplify the geologic history of the fault system in a Procrustean effort to "fit" the complex on-land record to that of the seafloor [see Powell (1992b) for discussion and references]. The rich complexity of the on-land record, on the other hand, provides evidence for a temporal and spatial disposition of faulting in the San Andreas system that has yet to be fully utilized in constraining models for the evolution of the plate boundary.

Onshore in California, the earliest phase of dextral shear was transtensional deformation and volcanism between 26 and 22 to 20 Ma (Stanley 1987a, Graham et al 1989, Yeats et al 1989); we find no evidence for a throughgoing strike-slip fault on land during this time interval (Powell 1992a). In southern and central California, the late Oligocene and the early Miocene were characterized by the structural growth of terrestrial and marine sedimentary and volcanic basins in a dextral shear regime. The timing and style of the tectonic transition between this transtensional phase and the emergence of a throughgoing strike-slip fault by late early Miocene (ca. 20 to 18 Ma) warrants further investigation. Either the structures of this early transtensional phase of deformation evolved into a throughgoing strike-slip fault by 20 to 17 Ma, or they provided an inherited framework, part of which the throughgoing fault followed. Relevant to the nature of this transition is a growing body of evidence that calls into question the presumed existence of a transform offshore along the continental margin of central California during this time interval (McCulloch 1987, Tennyson 1989).

Between 20 to 17 Ma and 13 to 12 Ma, the Clemens Well–Fenner–San Francisquito–San Andreas fault accumulated 100 to 110 km of displacement (Powell 1981, 1992a; Sims 1992) and major sinistral deformation occurred along the southern boundary of the Transverse Ranges either as an ancestral strike-slip fault or as a zone of sinistral deflection along the trend of the modern Malibu Coast, Santa Monica, Raymond, Cucamonga, and Banning faults (Campbell & Yerkes 1976, Silver 1982, Powell 1992a). Coeval dextral slip of ~180 km has been postulated along the East Santa Cruz Basin fault in the southern California continental borderland (Howell et al 1974, Howell 1976a) and several tens of kilometers of right-oblique shear have been documented along Walker lane east of the Sierra Nevada (Bohannon 1979, Stewart 1983, Dilles 1989). Within the context of the transform fault paradigm, displacement on the Clemens Well–Fenner–San Francisquito–San Andreas fault probably connected northwestward with the Mendocino triple junction, but its disposition to the southeast is problematic. Hypothetical scenarios for the southeastward disposition of displacement are shown in Figure 7 (summarized from Powell 1992a). In one scenario, dextral displacement on the Clemens Well–Fenner–San Francisquito–San Andreas fault stepped right to the continental margin to connect with the southward-migrating southern triple junction along a fault such as the East Santa Cruz Basin fault (Figure 7*a*). The required large right step would have taken place by means of the well-documented zone of coeval sinistral and extensional deformation along the southern boundary of the Transverse Ranges west of the San Andreas (Campbell & Yerkes 1976). In this scenario, favored by Powell (1992a), right-lateral displacement is transformed into left-oblique extensional tectonism across an extensional wedge perhaps analogous to that between the Death Valley and Garlock faults. In this scenario, extreme extension near the corners of the "Z" would provide a tectonic regime for exhuming, on coeval detachment faults, the deep-seated rocks of the Catalina Schist in the Los Angeles basin area and of Pelona and Orocopia Schists in the restored Sierra Pelona–Chocolate Mountains area.

In another scenario, displacement on the southeastward extension of the Clemens Well fault stepped right across the Chocolate Mountains to a hypothetical fault—near the current trace of the Salton trough segment of the San Andreas proper—which connected southward with the gulf region (Figure 7*b*). At present, there is a lack of evidence for the required displacement in the Salton trough (Powell 1992a), and for widespread extensional volcanism and tectonism in the Gulf of California region prior to about 12 to 14 Ma (Withjack & Jamison 1986, Lonsdale 1989, Stock & Hodges 1989, Humphreys & Weldon 1992)—although the evidence from some localities does not preclude extensional faulting having started prior to 14 Ma (Henry 1989). In the absence of strong supporting evidence, however, it seems unlikely that the Clemens Well–Fenner–San Francisquito–San Andreas fault extended into the gulf region.

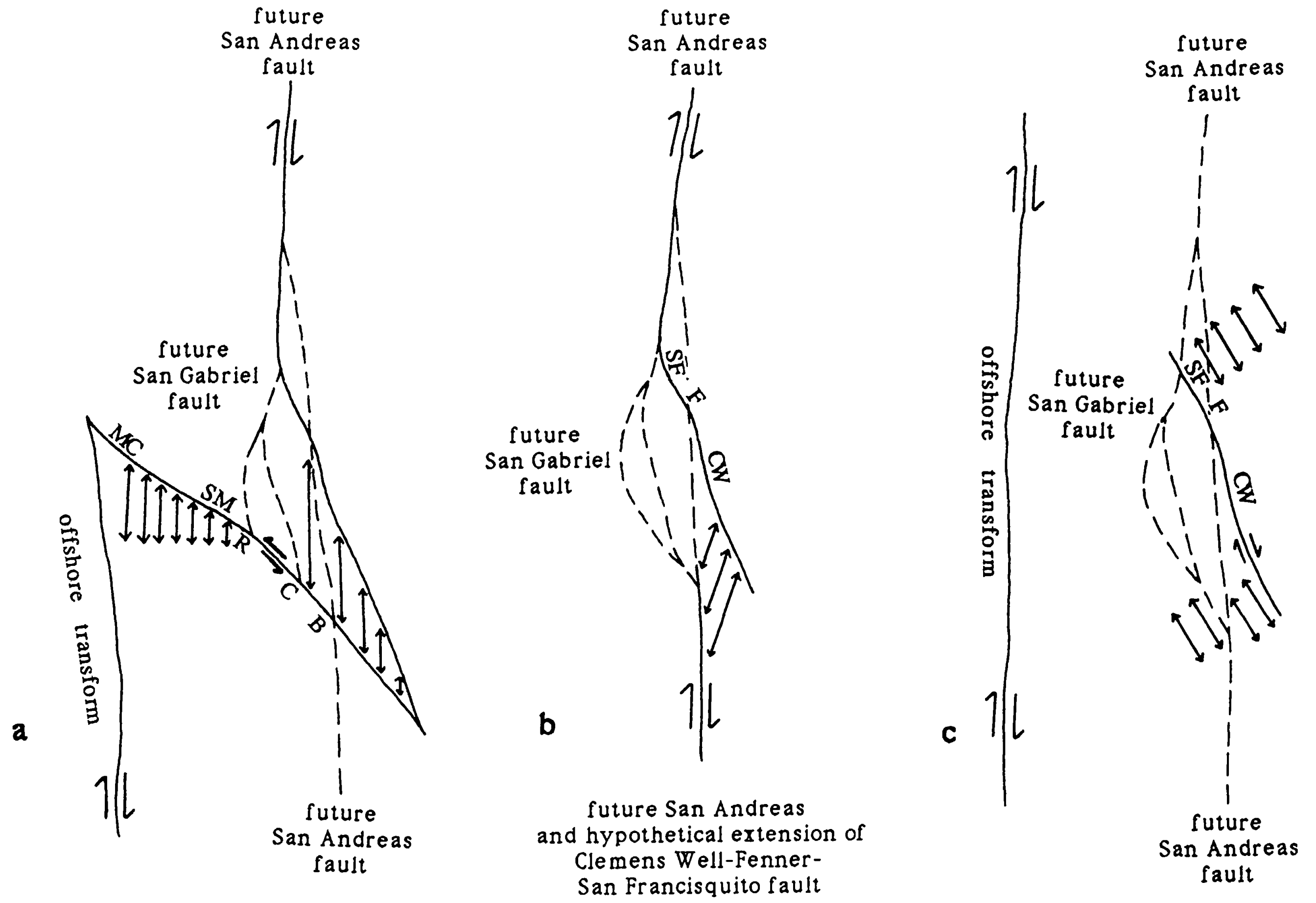


Figure 7 Models for the Clemens Well–Fenner–San Francisquito–San Andreas fault (after Powell 1992a). To the north, the dextral Clemens Well–Fenner–San Francisquito–San Andreas fault probably connected with the Mendocino triple junction. To the south, the disposition of displacement on the Clemens Well–Fenner–San Francisquito–San Andreas can be modeled in three ways: (*a*) right slip stepped west to the continental margin to connect with the southward migrating southern triple junction via an offshore transform fault—possibly the East Santa Cruz Basin fault of Howell et al (1974); (*b*) right slip stepped west to the area of the future Salton trough and Gulf of California; or (*c*) right slip was accommodated by extensional faulting in southeasternmost California and southwesternmost Arizona. B, Banning fault; C, Cucamonga fault; CW, Clemens Well fault; F, Fenner fault; MC, Malibu Coast fault; R, Raymond fault; SF, San Francisquito fault; SM, Santa Monica fault. Double-tipped arrows show extensional domains required by each model.

In a third scenario, the southeastward projection of the Clemens Well–Fenner–San Francisquito–San Andreas fault can be modeled as an intracontinental transform fault which accommodated differential displacement rather than connecting to the southern triple junction (Figure 7*c*). This tectonic setting is partly analogous to that proposed for the Garlock fault or the Las Vegas shear (Davis & Burchfiel 1973, Wernicke et al 1982), and this scenario requires that right-lateral displacement be transformed into Basin and Range type extensional faulting in southeasternmost California and southwesternmost Arizona. The viability of this scenario depends on the as yet undocumented existence of a regional extensional domain that projected south to southwest from the Clemens Well–Fenner–San Francisquito–San Andreas fault.

These possibilities provide testable alternatives in the timing and displacement across structures in southern California and the Gulf of California region, and more work should resolve the evolution of the tectonic setting of the fault zone. Whatever tectonic role the Clemens Well–Fenner–San Francisquito–San Andreas fault played, it accounts for ~100 km of displacement usually erroneously distributed to the modern San Andreas fault; removing this extra displacement provides a later history that is much more reasonable.

Between 13 to 11 and 6 to 4 Ma, the principal active right-lateral faults of the San Andreas system were the San Gabriel, San Gregorio–Hosgri, and Rinconada–Reliz faults and the San Andreas fault northwest of its intersection with the San Gabriel fault. The San Gabriel fault accumulated a displacement of 42 to 45 km that passed northward onto the central reach of the San Andreas fault, the Rinconada–Reliz fault accumulated a displacement of as much as ~45 km that probably passed northward onto the San Gregorio fault, and the San Gregorio–Hosgri fault accumulated a displacement of as much as 150 km that passed northward onto the northern reach of the San Andreas fault. To the north, these faults probably connected with the Mendocino triple junction via the San Andreas. To the south, where these dextral faults intersect the sinistral and reverse faults of the western Transverse Ranges, the disposition of displacements is controversial. The San Gregorio–Hosgri and Rinconada–Reliz faults abut the western Transverse Ranges: We find no evidence that these faults extend through or east of the western Transverse Ranges, and their displacements either are absorbed by an east-trending domain of left-oblique extension in the western Transverse ranges or are stepped right to the continental margin across such a domain.

The San Gabriel fault splits southward into several branches in the western and southern San Gabriel Mountains (Figure 3), where the disposition of its displacement can be modeled in different ways as shown in

Figure 8 [summarized from Powell (1992a), Weldon et al (1992)]. Typically, dextral slip on the San Gabriel fault is linked kinematically to right-oblique extensional tectonism associated with the proto–Gulf of California (Crowell 1981, Lonsdale 1989, Stock & Hodges 1989, Humphreys & Weldon 1991). However, although the displacement of 22 to 23 km on the San Gabriel fault in the San Gabriel Mountains (Ehlig 1975) probably extends west through San Gorgonio Pass (Matti & Morton 1992), where it connects with the Salton trough–Gulf of California region (Figure 8*a*), disposition of the remainder of the displacement on the San Gabriel fault is less clear. Southeastward projection of large dextral displacement along the south flank of the San Gabriel Mountains is not supported by disrupted paleogeologic patterns and is disallowed by the continuous distribution of the 15-m.y.-old Glendora Volcanics across the projected fault path. One alternative possibility is that dextral shear stepped west to the continental margin, causing left-oblique extension in the Los Angeles basin area (Figure 8*b*). Another possibility is that dextral motion stepped east to the Punchbowl–San Andreas fault, causing a transpressional step (Figure 8*c*) that could have uplifted the proto–Transverse Ranges in the late Miocene (Meisling & Weldon 1989, Weldon et al 1992). The best solution may be a combination of all three (Figure 8*d*), in which about half of the displacement stepped west in parallel with that on the San Gregorio–Hosgri and Rinconada–Reliz faults, a small amount stepped east where it was associated with the early growth of pull-apart basins along the Punchbowl–San Andreas fault, and up to half connected with the proto–Gulf of California.

In the central Transverse Ranges, the transition from the Clemens Well–Fenner–San Francisquito fault to the San Gabriel fault, as the principal strike-slip fault of the San Andreas system, was accompanied by an abrupt change in the structural and stratigraphic character of contemporaneous basins along the San Andreas fault (Weldon et al 1992). Basins contemporaneous with the Clemens Well–Fenner–San Francisquito fault were characterized by throughgoing drainage systems, far-traveled clast assemblages, and relatively broad distribution of facies; basins contemporaneous with the San Gabriel fault, on the other hand, were characterized by local relief and clast sources, and by abrupt facies changes. Moreover, the growth of the San Gabriel fault coincided with uplift and erosion of the ancestral San Bernardino Mountains and central San Gabriel Mountains (Figure 5).

Other faults that may have been active between 10 and 5 Ma include the Punchbowl fault, the Garlock fault, and some of the right-lateral faults of the north-central Mojave Desert. The pull-apart origin proposed for the Punchbowl and Mill Creek Formations implies that early right-oblique

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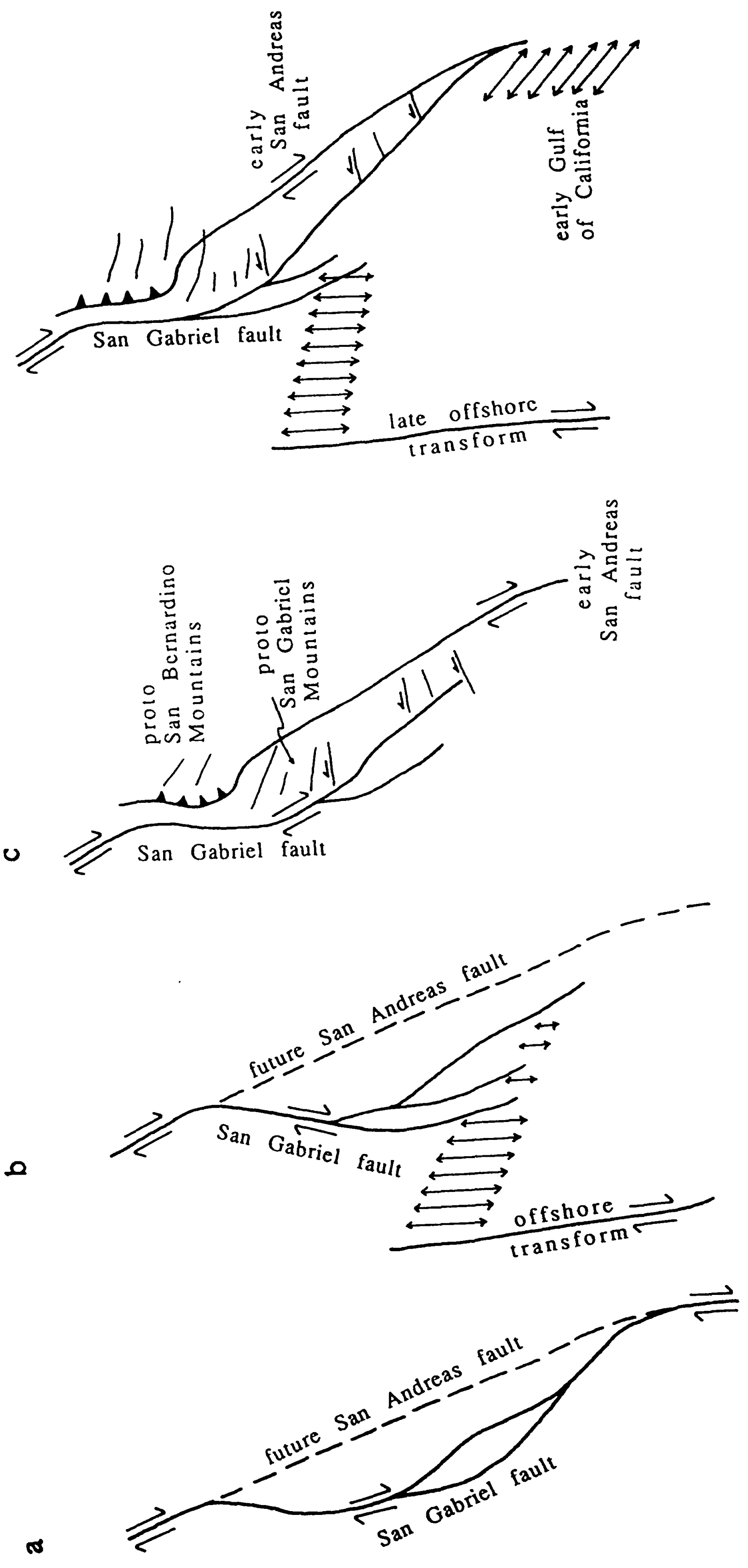

Figure 8 Models for the San Gabriel–San Andreas fault. After Powell (1992a) and Weldon et al (1992). To the north, the dextral San Gabriel–San Andreas fault connected with the Mendocino triple junction. To the south, disposition of displacement is problematic and can be modeled in four ways: (*a*) right slip merged eastward with the future trace of the San Andreas fault; (*b*) right slip stepped west to the continental margin to connect with the southward migrating southern triple junction; (*c*) right slip stepped east to the incipient Punchbowl–San Andreas fault; or (*d*) a combination of (*a*) to (*c*). Double-tipped arrows show extensional domains required by each model: Extensional domains between the San Gabriel fault and the offshore transforms in (*b*) and (*d*) are left-oblique; extensional domain in early Gulf of California region in (*d*) is right-oblique.

shear occurred on the Punchbowl fault or near the trace of the San Andreas fault in the vicinity of the pull-apart basins. As inferred from stratigraphic and paleomagnetic evidence, the Garlock fault may have begun to move at 9 or 10 Ma (Carter 1987, Loomis & Burbank 1988) and some of the right-lateral faults in the Mojave Desert may have begun to move between 10 and 6 Ma (Dokka & Travis 1990a).

Since 4 to 6 Ma, the major active right-lateral fault has been the San Andreas fault proper, which has accumulated a displacement of 150 to 160 km. The San Andreas proper in and south of the Transverse Ranges formed as the link between the San Andreas fault north of its junction with the San Gabriel fault and the opening Gulf of California. The rapid acceleration of slip rate to 35 mm/yr at 4 to 5 Ma signals the establishment (or reestablishment if the Clemens Well–Fenner–San Francisquito fault is considered part of the San Andreas) of the San Andreas fault as the dominant fault in the plate boundary. The jump in the locus of seafloor spreading into the Gulf of California at this time (Atwater 1970, 1989; Lonsdale 1989; Stock & Hodges 1989) is unquestionably related kinematically to acceleration of slip on the San Andreas fault. The apparently constant slip rate since indicates that the basic kinematics of the plate boundary seen today (Figure 9) have persisted for the past 4 to 5 Ma. Humphreys & Weldon (1992) speculated that there was a change in the coastal fault system around 2 Ma; slip that now crosses the northern Baja Peninsula (trans-peninsular faults, Figure 9)—and is kinematically related to the high rate of Quaternary deformation in the western Transverse Ranges and Los Angeles basin region—may have extended farther down the coast and connected to the plate boundary in or south of southern Baja. The magnitude of deformation extending to the San Andreas system from the gulf does not appear to have changed at this time.

Since its inception, the San Andreas fault proper has slipped at less than the plate rate of 48 mm/yr. In southern and central California between Cajon Pass and the Gabilan Range, the San Andreas fault has slipped at 35 mm/yr, whereas north and south of that segment the San Andreas fault proper has slipped at 20 to 25 mm/yr. The plate motion deficit is being accommodated by at least three mechanisms that operated coevally with the Pliocene and Quaternary San Andreas fault (Minster & Jordan 1978; Fox et al 1985; Weldon & Humphreys 1986; U.S. Geological Survey 1990; Ward 1990; Humphreys & Weldon 1991, 1992; Lisowski et al 1991): (*a*) A subordinate system of right- and left-lateral strike-slip faults developed including, from south to north, dextral faults in the Peninsular Ranges and possibly in the continental borderland, sinistral faults in the Transverse Ranges, dextral faults in the Mojave Desert, the sinistral Garlock fault, dextral faults in the Death Valley area, and the dextral Calaveras–Hayward

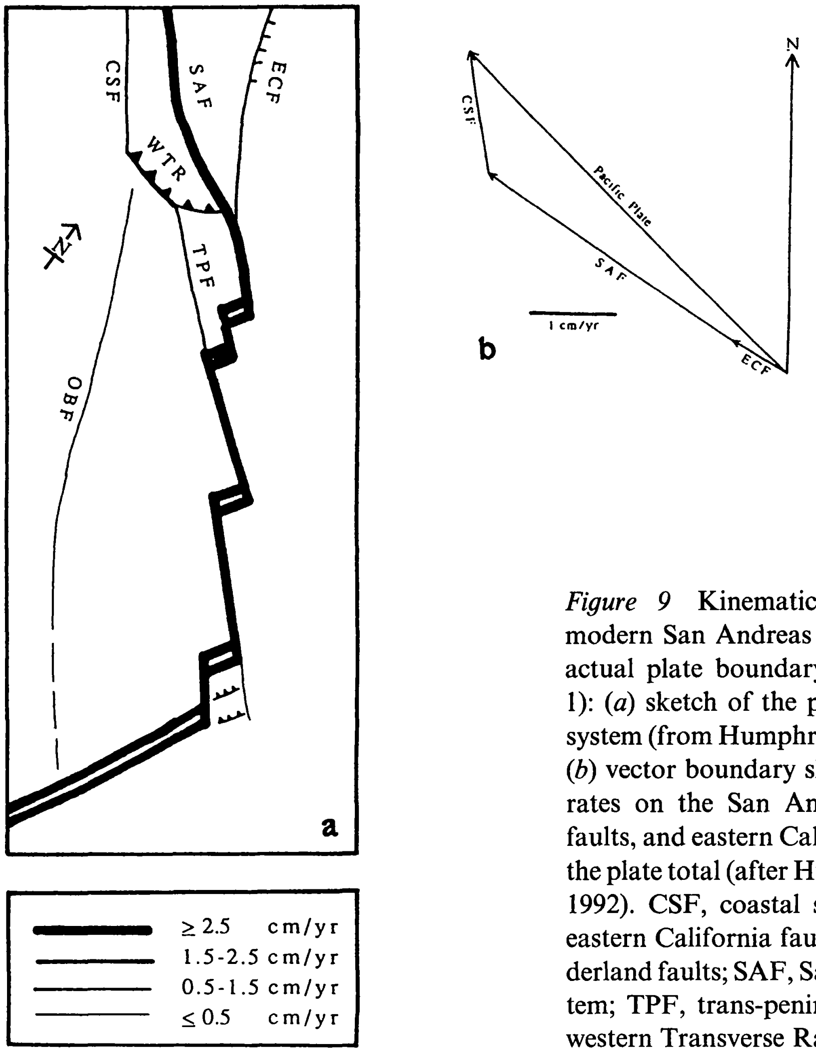

Figure 9 Kinematic relations for the modern San Andreas fault modeled from actual plate boundary structures (Figure 1): (*a*) sketch of the plate boundary fault system (from Humphreys & Weldon 1991); (*b*) vector boundary showing how the slip rates on the San Andreas fault, coastal faults, and eastern California faults sum to the plate total (after Humphreys & Weldon 1992). CSF, coastal system faults; ECF, eastern California faults; OBF, outer borderland faults; SAF, San Andreas fault system; TPF, trans-peninsular faults; WTR, western Transverse Ranges deformation.

fault. (*b*) Oblique contractional structures have developed in the Transverse Ranges (≤ 23 mm/yr) and in the southern Coast Ranges (≤ 5 mm/yr). (*c*) The Basin and Range province underwent right-oblique extension (~ 8 mm/yr).

In Figure 9, the sketch and vector diagram (modeled from the map in Figure 1) of the faults of the San Andreas system highlight a three-fold division of the plate boundary in California since 4 to 5 Ma. The San Andreas fault provides the most direct connection between the two triple junctions and is most active, but much deformation also occurs on subparallel zones to the east and west (Figures 1 and 9*a*). The San Andreas system and the coastal fault system, particularly near the Transverse Ranges, trend more westerly than the motion across them, so they are transpressional. The eastern California system trends more northerly and is transtensional. The vector diagram (Figure 9*b*) is the sum of the three zones at the latitude of the Transverse Ranges, and shows how the three zones sum to the plate boundary total.

Prior to 4 to 5 Ma, the San Gabriel–San Andreas and Clemens Well–Fenner–San Francisquito–San Andreas faults constituted even smaller fractions of published estimates for total plate motion (Engebretson et al 1985, Stock & Molnar 1988, Atwater 1989) than the modern San Andreas does. The distribution of the rest of the plate motion between about 20 and 5 Ma is not well established. Although it has been shown that Walker lane and perhaps the northern Mojave Desert accommodated right-oblique shear between 20 and 5 Ma (Wernicke et al 1982; Stewart 1983; Dilles 1989; Dokka & Travis 1990a,b), these displacements have yet to be integrated with those of the San Andreas system to balance the strain budget for the pre–5 Ma plate boundary. Inasmuch as the geometrical model for transform growth predicts the existence of a transform fault along the actual edge of the North American plate, one might expect to find an early dextral fault of the San Andreas transform system along the boundary between continental and oceanic crust offshore from southern and central California (Dickinson 1981). Although such a fault would have accommodated part of the plate motion, no transform fault has been identified along the continental margin. On the contrary, the boundary between oceanic and continental crust is interpreted as an inactive east-dipping low-angle fault, along which oceanic crust was subducted beneath the west edge of the North American plate prior to overlap by undeformed Miocene strata (McCulloch 1987, Irwin 1990).

CONCLUSIONS

The San Andreas fault system constitutes a largely intracontinental plate boundary between the North American and Pacific plates. The San Andreas fault itself, with the largest displacement and highest slip rate of any fault in the system, is the principal link between the Mendocino junction and the seafloor system of spreading axes and transforms in the Gulf of California.

Existing transform fault models for the evolution of the San Andreas system are inconsistent with many findings on displacement, timing of movement, and slip rate for the faults of the San Andreas system. Palinspastic reconstruction of paleogeologic features that evolved during and prior to the evolution of the fault system shows that throughgoing intracontinental faults of the San Andreas system emerged at 20 to 17 Ma and evolved in at least three distinct phases. In the earliest phase, between 20 to 17 Ma and 13 to 12 Ma, the Clemens Well–Fenner–San Francisquito–San Andreas fault accumulated a displacement of 100 to 110 km at an average rate in the range of 10 to 30 mm/yr.

In the middle phase, between 13 to 12 Ma and 6 to 4 Ma, the San Gabriel, Rinconada–Reliz, and San Gregorio–Hosgri faults developed southwest of the Clemens Well–Fenner–San Francisquito–San Andreas fault with a more northerly strike than that fault. Northwest of their junctions with the earlier fault, displacement on the new faults passed onto the San Andreas segment of the earlier fault; southeast of its junction with the San Gabriel fault, the Clemens Well–Fenner–San Francisquito segment of the earlier fault was abandoned. The San Gabriel fault accumulated a displacement of 42 to 45 km at a rate in the range of 5 to 10 mm/yr.

In the latest evolutionary phase of the San Andreas system, the modern San Andreas fault emerged at 5 to 4 Ma as a link between the nascent Gulf of California and the Mendocino triple junction. The San Gabriel fault was largely abandoned, but the Rinconada–Reliz and San Gregorio–Hosgri faults continued to accumulate displacement. The slip-rate on the San Andreas fault (20 to 35 mm/yr) during this phase consistently has been less than the plate rate, resulting in the growth of other structures to help accommodate the full plate movement. These other structures include a subordinate system of conjugate strike-slip faults, oblique contractional structures in the Transverse and Coast Ranges, and oblique extensional structures in the Basin and Range province.

Although it provides an appealingly simple plate tectonic framework for the existence of the San Andreas fault system, assigning a transform role to the San Andreas system raises questions about why the San Andreas fault system developed intracontinentally rather than along the boundary between oceanic and continental crust. By considering the transform fault paradigm for the Pacific–North American plate boundary from the perspective of this three-phase evolution for the San Andreas fault system, we can look for ways to further our understanding of why the San Andreas system evolved as a transform.

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