The San Andreas fault is a transform fault along the boundary between the Pacific and North American plates. Bedrock along the fault includes various lithologic units that range in age from Precambrian to Tertiary and younger. Some bedrock units that can be matched across the fault suggest strike-slip displacement of as much as 560 km.

3. GEOLOGY AND PLATE-TECTONIC DEVELOPMENT

By William P. Irwin

CONTENTS

Introduction ........................................ Page
Geologic formations ................................ 61
Northern and central California ....................... 63
Franciscan rocks ...................................... 63
Coast Range ophiolite ................................ 64
Great Valley sequence ................................ 64
Coast Range thrust ................................... 65
Salinian block ....................................... 66
Displacement of pre-Quaternary rocks by the San
Andreas fault ....................................... 67
Relation of geologic structure to seismic behavior 68
Southern California ................................... 70
Transverse Ranges and the Salton Trough .......... 70
Displacement of basement rocks by the San
Andreas fault ....................................... 72
Plate-tectonic development of the San Andreas fault 73
References cited ..................................... 77

INTRODUCTION

The great scar across the land of California, extending from the Gulf of California to Point Arena on the north coast, was recognized as a major fault during early geologic study of the San Francisco peninsula; it was named for San Andreas Valley, which lies a few kilometers south of San Francisco. Interest in the San Andreas fault was heightened as a result of movement on the fault, in some places as much as 5 m of strike-slip displacement, that occurred during the great San Francisco earthquake of 1906. Because of this earthquake, a concerted study was carried out by several leading geologists of that time (Lawson, 1908) that dramatically increased our knowledge of the regional extent and general features of the fault. Much controversy ensued during the following decades as to the time of origin of the fault, the magnitude of cumulative displacement along it, and, indeed, even whether the displacement might be principally dip slip rather than strike slip. An early proponent of substantial lateral movement on the San Andreas fault was Levi Noble (1927) of the U.S. Geological Survey, who suggested a 38-km right-lateral displacement based on the similarity of Tertiary strata on opposite sides of the San Andreas fault at Cajon Pass and Rock Creek (lat 34°28' N., long 117°30' W.). Substantial lateral offset of Quaternary terraces along the Mojave segment of the fault was recognized by R.E. Wallace (1949) while working on his Ph.D. thesis at the California Institute of Technology. He estimated a slip rate of 0.4 cm/yr, which he extrapolated to 120 km of right-lateral slip since mid-Tertiary time (approx 30 Ma). In 1953, a benchmark

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\*Figure 3.1—Sequential diagrams showing interactions between the North American, Parallon, and Pacific plates, assuming a constant relative motion of 6 cm/yr parallel to the San Andreas fault (modified from Atwater, 1970). Position of the North American plate in each time frame is relative to those of the Parallon and Pacific plates rather than to outlines of diagram. Lengthening interface between the North American and Pacific plates, shown in three upper diagrams, represents the San Andreas transform fault. Captions for each step indicate amount of time and lateral movement necessary for the North American plate to reach its present position relative to the Pacific plate. GS, Guaymas; MZ, Mazatlán; S, Seattle; SF, San Francisco.

THE SAN ANDREAS FAULT SYSTEM, CALIFORNIA: U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1515
EXPLANATION

Spreading center—
Dashed where
approximately
located. Arrows
indicate direction
of movement

Subduction zone—
Sawtooth on upper
plate

Fault—Arrows indicate
direction of relative
movement

PRESENT

NORTH AMERICAN PLATE

PACIFIC PLATE

10 m.y.
600 km

NORTH AMERICAN PLATE

PACIFIC PLATE

20 m.y.
1200 km

NORTH AMERICAN PLATE

PACIFIC PLATE

30 m.y.
1800 km

NORTH AMERICAN PLATE

PACIFIC PLATE

40 m.y.
2400 km

PACIFIC PLATE
During middle and late 1960's, a time of great ferment of concepts regarding the plate-tectonic development of the planet Earth, the foundation was laid for much of the present view of the tectonics of California and the San Andreas fault. A highly significant breakthrough to our understanding of the development of the fault system was the brilliantly simple construction by J. Tuzo Wilson (1965, fig. 9), who showed the San Andreas fault as a transform fault connecting two spreading oceanic ridges (figs. 3.1, 3.2). This view was soon modified by McKenzie and Morgan (1969) and Atwater (1970) to account for the effects of migrating triple junctions and for the timing, rates, and vectors of plate movement. Their plate-tectonic analysis of the San Andreas fault was based on calculations of plate motions between North America, Africa, India, Antarctica, and the Pacific, and many land-based geologists of the time would have agreed that it seemed "outrageous" to be "studying the San Andreas fault by using data that is no closer to California than 7,000 km" (Atwater and Molnar, 1973).

GEOLeGIC FORMATIONS

On its path through nearly the length of California, the San Andreas fault separates major crustal blocks (fig. 3.3). In much of northern and central California, the fault is a southeast-trending boundary between the Salinian block of granitic and metamorphic rocks on the west and the Franciscan assemblage and overlying strata of the Great Valley sequence on the east. In its southerly course the fault abruptly curves eastward to cut diagonally across the Transverse Ranges, and then splays into several auxiliary faults before the main strand terminates near the Gulf of California. In southern California the basement rocks cut by the San Andreas fault are mostly Precambrian and younger metamorphic and plutonic rocks, and the crustal blocks on either side of the fault generally do not show the distinctive lithologic contrast that is so striking in central and northern California.

![Geologic sketch map of California, showing distribution of principal basement rocks. Cenozoic cover not shown except for the Modoc Plateau, northeastern Sierra Nevada, Great Valley, and Santa Barbara-Ventura Basin. Based on U.S. Geological Survey (1966), Jennings and others (1977), and Ross (1984). Units: 1, Quaternary alluvium—shown only in Great Valley; 2, basement rocks concealed by thick Cretaceous and Tertiary deposits in the Santa Barbara, Ventura, and Los Angeles Basins; 3, Cenozoic volcanic rocks of the Modoc Plateau; 4, Great Valley sequence—Lower Jurassic to Upper Cretaceous strata, including Coast Range ophiolite at base; 5, Franciscan assemblage of Lower Jurassic to Tertiary oceanic rocks; 6, Sierra Nevada batholith—dominantly Cretaceous granitic rocks; 7, Sierra Nevada metamorphic belt—early Paleozoic to Late Jurassic rocks, including fragments of ophiolite, island arcs, and melanges, intruded by Mesozoic plutons; 8, Klamath Mountains—early Paleozoic to Late Jurassic ophiolite, island arcs, and melanges, intruded by early Paleozoic to Cretaceous plutons; 9, Salinian block—dominantly Cretaceous plutons intruding metamorphic rocks of questionable age (Barrett Ridge slice [BRS], commonly shown as part of the Salinian block, is here shown as part of unit 11); 10, southern California batholith—dominantly Cretaceous plutons intruding sedimentary and volcanic rocks of Jurassic age and metamorphic rocks of mostly unknown age; 11, mainly Precambrian metamorphic and plutonic rocks, in part overlain by Paleozoic continental shelf deposits and intruded by Mesozoic plutons, locally underthrust in southwestern part of region by schist (similar in lithology to the Pelous Schist) of probable Cretaceous age.]
NORTHERN AND CENTRAL CALIFORNIA

FRANCISCAN ROCKS

Franciscan rocks form the east wall of the San Andreas fault for virtually its entire course through the Coast Ranges of central and northern California, although the Franciscan is concealed along some reaches of the fault by overlying rocks. The Franciscan is a heterogeneous assemblage that consists largely of dismembered sequences of graywacke, shale, and lesser amounts of mafic volcanic rocks, thin-bedded chert, and rare limestone.
These rocks also occur with serpentinite and tectonic pods of blueschist in melange zones that are the locus of much shearing within the Franciscan and that generally separate blocks of the more coherent sequences. The sedimentary and volcanic Franciscan rocks were formed in a marine environment, as attested by the abundance of foraminifers in the limestone and by radiolarians in the chert. Most of these rocks are probably Late Jurassic and Cretaceous in age (Bailey and others, 1964), but some of the chert and associated volcanic rocks are as old as Early Jurassic (Pliensbachian) (Irwin and others, 1977; Blome and Irwin, 1983). In the northern Coast Ranges, some of the rocks assigned to the coastal belt of the Franciscan assemblage are as young as late Tertiary and are thought to have accreted to North America during post-middle Miocene time (McLaughlin and others, 1982). The age and origin of Franciscan melange is problematic. Mid-Cretaceous limestone in melange near Laytonville in the northern Coast Ranges, 225 km northwest of San Francisco, has a paleomagnetic inclination that indicates an origin several thousand kilometers to the south (Alvarez and others, 1980). Similarly, Franciscan pillow basalt about 45 km northwest of San Francisco is thought to have moved northward 19° of latitude (approx 2,000 km) from its site of origin (Grommé, 1984). These and other features indicate that some, possibly much, of the Franciscan has been transported great distances northward along the Pacific margin relative to a stable North America.

The Franciscan rocks are locally overlain structurally by the Coast Range ophiolite and the Great Valley sequence, and are separated from them by the Coast Range thrust (Bailey and others, 1970). The original extent of the Coast Range thrust is not clearly known because most of the ophiolite and Great Valley sequence that formed the upper plate of the thrust has been removed from the top of the Franciscan except in the general area of the Diablo antiform, which is marked by a line of windows from Mount Diablo to Parkfield, and along the west edge of the Great Valley (figs. 3.3, 3.4). A few small outliers of upper-plate rocks are present elsewhere east of the San Andreas fault as far north as Pillsbury Lake, 35 km east of Willits, and the Camp Meeker area, 17 km northeast of Bodega Head, and at several localities west of the Salinian block as far south as the Santa Ynez fault in the Transverse Ranges (see maps at front of book). Much of the serpentinite in Franciscan melange may well be sheared-in fragments of dismembered Coast Range ophiolite.

**COAST RANGE OPHIOLITE**

The Coast Range ophiolite represents oceanic crust on which much of the sedimentary rock of the Great Valley sequence was deposited. A complete ophiolite sequence consists of serpentinized harzburgite tectonite at the base, overlain by cumulate ultramafic and gabbroic rocks, passing upward into noncumulate gabbroic and related plutonic rocks, then into diabase dikes, and finally into pillow lavas. The Coast Range ophiolite, however, generally is highly sheared, dismembered, thinned, and locally missing, presumably as a result of faulting, at many places along the fault contact between Franciscan and Great Valley rocks. Only in a few places is a nearly complete lithologic sequence of Coast Range ophiolite preserved, and there the total stratigraphic thickness of the ophiolite is about 3 to 5 km (Hopson and others, 1981). Isotopic ages ranging from about 165 to 153 Ma (Hopson and others, 1981) indicate that the Coast Range ophiolite is Middle and Late Jurassic in age. Paleontologic and paleomagnetic evidence suggests that the Coast Range ophiolite formed in an equatorial setting and was transported great distances northward before being accreted to North America and overlain by the Great Valley sequence (Pessagno and others, 1964; Hopson and others, 1986; McLaughlin and others, 1988).

**GREAT VALLEY SEQUENCE**

The Great Valley sequence consists of interbedded marine mudstone, sandstone, and conglomerate that range from Late Jurassic to Cretaceous in age (Bailey and others, 1964). It crops out as thick, monotonously bedded sections of strata that generally are markedly less deformed and more coherent than sedimentary sections of the Franciscan and also have greater lateral continuity. Where most fully developed, such as along the west side of the northern Great Valley, the aggregate stratigraphic thickness of Great Valley sequence is at least 12 km. The strata normally lie depositionally on Coast Range ophiolite except where disrupted by faults, but at the north end and along the east side of the Great Valley they onlap the Nevada and older basement terranes of the Klamath Mountains and Sierra Nevada.

This enormous thickness of elastic detrital material probably represents submarine fans and turbidity deposits that formed as a result of rapid erosion of the ancestral Klamath Mountains and Sierra Nevada.

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**Figure 3.4.** — Schematic block diagram of part of the Coast Ranges of California, showing gross structural relations between principal lithotectonic units cut by the San Andreas fault (modified from Irwin, 1977). The Coast Range ophiolite lies at base of the Great Valley sequence and is separated from underlying Franciscan rocks by the Coast Range thrust. Blueschist-facies metasedimentary and metavolcanic rocks that form border zone in the Franciscan immediately below the thrust are not shown. View southeastward along the San Andreas fault.
COAST RANGE THRUST

The upper plate of the Coast Range thrust, consisting of Great Valley sequence with Coast Range ophiolite at the base, is cut by the San Andreas fault only along the west side of the Diablo Range in central California. There, the upper plate of the Coast Range thrust forms a broad blanket over the Franciscan rocks except in

EXPLANATION

- Great Valley sequence and Coast Range ophiolite at base
- Salinian block
- Franciscan assemblage
- Upper Cretaceous and Tertiary strata
- Fault—Dotted where concealed; arrows indicate direction of relative movement.

G, Calaveras; H, Hayward; S, Sargent
several places along the length of the Diablo Range where windows, or piercement structures, in the upper plate expose Franciscan rocks of the lower plate (fig. 3.4: at Mount Diablo, Pacheco Pass, New Idria, and Parkfield. This deformed antiformal structure (Bailey and others, 1964) is truncated on the west by the Hayward and Calaveras faults in its northern part and by the San Andreas fault in its southern part, and narrows to the southeast as the San Andreas fault converges with the south end of the Great Valley. The ophiolitic rocks are generally thinned and highly discontinuous along the faults that bound the windows except for the New Idria window, which is occupied mostly by serpentinite. South of the Pacheco Pass window, the structure is complicated by a series of west-northwest-trending synforms that cross the axis of the Diablo Range antiform at a low angle, and by multiple strands of the San Andreas fault. In the Parkfield area, the western part of the antiform has been virtually destroyed by its proximity to the San Andreas fault. The Franciscan rocks of the Parkfield window, and the associated serpentinite and Great Valley sequence of the highly dissected upper plate, now are mostly elongate fault slices that form part of the San Andreas fault zone (see Dibblee, 1980).

Most of the serpentinite of the Coast Ranges of California is related to the ultramafic parts of the Coast Range ophiolite. Serpentinite is strikingly absent along the San Andreas fault north of San Francisco, a situation that reflects the absence of the upper plate of the Coast Range thrust in that area. Although many elongate fault-bounded bodies of serpentinitized ultramafic rocks in the Coast Ranges traditionally have been mapped and described as part of the Franciscan, most are probably dismembered and dislocated parts of the Coast Range ophiolite or equivalent. Recognition that the ultramafic rocks in most places belong to the Coast Range ophiolite rather than to the Franciscan assemblage is important to a tectonic analysis of the region. The common presence and possible seismotectonic significance of serpentinite along creeping segments of the San Andreas and related faults were described by Allen (1968) and Irwin and Barnes (1975).

SALINIAN BLOCK

The west wall of the San Andreas fault consists mainly of rocks of the Salinian block from the Transverse Ranges northward to Bodega Head. At the latitude of the San Francisco peninsula, the Salinian block is separated from the San Andreas fault by a narrow fault slice of Franciscan rocks (fig. 3.3). Northward, from just beyond Bodega Head to Point Arena, the rocks that crop out along the fault are chiefly Upper Cretaceous and Tertiary sedimentary strata, but because of the presence of a relatively small exposure of spilitic volcanic rocks that may be Franciscan, it is questionable whether these sedimentary rocks overlie granitic and metamorphic rocks of the Salinian block or whether they are separated from the Salinian block by another fault just off shore (Wentworth, 1968). The north end of the Salinian block off shore is thought to be at about the latitude of Point Arena (see McCulloch, 1987). At Point Delgada (see maps at front of book), which many workers consider to be the location of the northernmost onland trace of the San Andreas fault, the rocks on both sides of the fault are Franciscan.

The Salinian block is composite, consisting of central, western, and northern belts, and commonly is considered to include the Barrett Ridge slice (fig. 3.3; Ross, 1984). The basement rocks of the Barrett Ridge slice, though poorly exposed, are thought likely to be a northward continuation of the rocks of the San Gabriel Mountain area because they include similar appearing metamorphic and granitic rocks, as well as schist similar to the Pelona Schist, along a possible exposure of the Vincent (?) thrust (Ross, 1984). The principal formations of these central, western, and northern belts are granitic and metamorphic rocks, locally overlain by Upper Cretaceous and younger strata. The metamorphic rocks, which commonly are moderate- to high-grade gneiss, granofels, impure quartzite, and minor schist and marble, probably represent a metamorphosed thin-bedded sequence of siltstone and sandstone, with lesser amounts of shaly, marly, and calcareous strata (Ross, 1978). The metamorphic rocks of the western belt are higher in metamorphic grade than those of the central and northern belts. The stratigraphic age of the protoliths of the metamorphic rocks is not known. The plutonic rocks are mostly granite and tonalite, but they range in composition to gabbro. U-Pb-isotopic measurements on zircon in the plutonic rocks indicate that plutonic activity began about 120–105 Ma in the northwestern part of the Salinian block and migrated southeastward over a period of 40 m.y., with the youngest plutons intruding the Barrett Ridge slice about 80–75 Ma (Mattinson and James, 1985).

The basement rocks of much of the Salinian block do not clearly differ from those of the Sierra Nevada, and so many workers have speculated that the Salinian block may be a displaced part of the Sierra Nevada (for example King, 1959; Page, 1981). According to Ross (1984), who compared the two terranes in considerable detail, the similarities are so great that strong data would be required to support an alternative origin. Paleomagnetic data, however, indicate that the Salinian block may have been displaced 2,500 km northward since Cretaceous time (Champion and others, 1984) and that it may have originated near the latitude of Central America or Mexico in the axial part of the Cordilleran Cretaceous plutonic arc (Page, 1982).
3. GEOLOGY AND PLATE-TECTONIC DEVELOPMENT

DISPLACEMENT OF PRE-QUATERNARY ROCKS BY THE SAN ANDREAS FAULT

The largest offset on the San Andreas fault postulated by Hill and Dibblee (1953) is 560 km, on the basis of the speculation that a contact between Sierran basement and Franciscan rocks near the south end of the Great Valley was cut by the fault and that the contact on the west side of the fault was offset northward to a point at sea north of Point Arena. This concept, however, is questionable not only because of the uncertain correlation of the Salinian block with rocks of the Sierra Nevada but also because the northernmost exposure of granitic rocks along the west side of the fault is at Bodega Head, about 90 km southeast of Point Arena, and neither the presence nor the type of a contact between Sierran-type basement and Franciscan rocks is known off shore north of Point Arena (see McCulloch, 1987). Nor is the significance clearly known of the possibly substantial lateral offset along the San Gregorio fault, which intersects the San Andreas at a low angle just west of the entrance to the San Francisco Bay. However, Upper Cretaceous strata that crop out near Gualala, on the west side of the San Andreas fault between Bodega Head and Point Arena, were thought by Ross and others (1973) also to have been offset 560 km, consistent with Hill and Dibblee’s concept. The strata near Gualala include quartz-plagioclase arkose and a conglomerate characterized by unusual quartz-bearing mafic clasts, including volcanic rocks, diabase, and diorite to gabbro. Paleocurrent features indicate a source to the east of the fault. The source of the unusual gabbroic clasts is thought to be the Eagle Rest Peak area in the San Emidio Mountains, just east of the San Andreas fault in the Transverse Ranges (fig. 3.5). This area may also be the source of relatively small fault slivers of similar mafic rocks that now lie 160 km northwest along the San Andreas fault at Gold Hill and 320 km northwest at Logan (Ross and others, 1973).

FIGURE 3.5.—Locations of some pre-Quaternary features offset by the San Andreas fault in the California Coast Ranges. The La Honda Basin is an offset segment of the San Joaquin sedimentary basin (Stanley, 1987); boundary dashed where approximately located. Circled x's, bedrock exposures of unusual quartz-bearing mafic rocks at Logan, Gold Hill, and Eagle Rest Peak (Ross and others, 1973); squares, locations of the Pinnacles and Neenach Volcanic Formations (see fig. 3.6) (Matthews, 1976). Numbered dots: 1, Butano Sandstone and Point of Rocks Sandstone Member (of Kreyenhagen Formation), representing offset parts of an Eocene deep-sea fan (Clarke and Nilsen, 1973); 2, steeply southwest-dipping slopes of the San Joaquin and La Honda Basins during late Eocene time (Stanley, 1987); 3, deepest parts of the San Joaquin and La Honda Basins adjacent to the San Andreas fault during Saucian time (Stanley, 1987); 4, unusual clasts in upper Miocene conglomerate in the Temblor Range east of fault and their postulated source area in the Gabillian Range west of fault (Huffman, 1972).
their south limit in the Temblor Range; (2) Eocene formations in the Santa Cruz Mountains, offset 360 km from lithologically and faunally similar formations in the Temblor-San Emigdio Mountains; (3) sequences of lower Miocene volcanic rocks, red beds, and Oligocene and lower Miocene marine deposits of the Gabilian Range, offset 280 km from similar sequences in the San Emigdio Mountains; (4) a facies transition from marine to continental middle and upper Miocene beds of the Carrizo Plain, offset 104 km from a similar transition projected from the south end of the Great Valley; and (5) 16 km of offset based on the juxtaposition of two facies of Pleistocene gravel south of the Temblor Range.

Offset of the Eocene formations was described in more detail by Clarke and Nilsen (1973), who considered the lower to upper Eocene sedimentary sequences to represent parts of a single deep-sea fan that have been offset 305 km along the San Andreas fault. These sequences are (1) the Twobar Shale Member of the San Lorenzo Formation and the Butano Sandstone, exposed in the Santa Cruz Mountains on the west side of the fault; and (2) the shale member and Point of Rocks Sandstone Member of the Kreyenhagen Formation, exposed along the southwest boundary of the Great Valley on the east side of the fault (fig. 3.5). Both sandstone units, which consist chiefly of detritus from the Salinian block, are thought to have been deposited as a submarine fan on the west side of a deep, northwest-trending offshore basin.

The Eocene fan deposits on the east side of the fault are in a structurally complex area at the south end of the Diablo antiform. If they overlie Franciscan basement there and Salinian basement on the west side of the fault, they indicate that the Franciscan and Salinian basements had already been juxtaposed by Eocene time when the fan was deposited, as noted by Page and Engebretson (1984).

The strongest evidence for measuring the large amount of right-lateral displacement along the trace of the San Andreas fault through the Coast Ranges may be the correlation of the Pinnacles and Neenach Volcanic Formations (Matthews, 1976), which are exposed on opposite sides of the fault about 315 km apart (fig. 3.5). The Pinnacles Volcanic Formation is in the central Coast Ranges, on the west side of the Chalone fault, a parallel strand that is several kilometers west of the San Andreas. The Neenach Volcanic Formation is in the Mojave Desert, adjacent to the San Andreas fault on the northeast side, about 20 km southeast of its intersection with the Garlock fault. The volcanic rocks at both exposures rest on granitic basement rocks that are petrographically and chemically similar (Ross, 1984). As described by Matthews (1976), the volcanic rocks form stratigraphic sections that are remarkably similar in composition, lithologic sequence, and age; they consist of calc-alkaline andesite, dacite, and rhyolite flows interbedded with pyroclastic and volcanioclastic rocks (fig. 3.6). K-Ar isotopic analyses of the volcanic rocks indicate an early Miocene age (23.5 Ma; Turner, 1970). The similarity of the 315-km offset of the volcanic formations and the 305-km offset ascribed to the previously mentioned Eocene fan deposits suggests that little movement occurred along that section of the San Andreas fault during intervening Oligocene time (Clarke and Nilsen, 1973).

Paleobathymetric contour maps of middle Tertiary (late Oligocene to early Miocene) topographic features of the San Joaquin sedimentary basin match similar features across the fault in the La Honda Basin (fig. 3.5), according to Stanley (1987). The paleobathymetry is based on studies of the distribution of fossil foraminifers. In both basins, (1) the southwestern margins were bounded by shelf areas and steep north-facing slopes, (2) maximum water depth was about 2,000 m, (3) the deepest part was truncated by the San Andreas fault, and (4) the paleobathymetric contours generally trend at large angles to the fault and are truncated by it. These features indicate a post-late Zemorrian (late Oligocene to early Miocene) displacement of 325 to 330 km and a post-Saucesian (early Miocene) displacement of 320 to 325 km.

Large offset along the San Andreas fault is also indicated by an anomalous distribution of upper Miocene sedimentary deposits that occur on both sides of the fault for more than 300 km in the central Coast Ranges. According to Huffman (1972), the clast composition of upper Miocene sedimentary rocks of the Temblor Range lying east of the fault in the southern Coast Ranges indicates that they were deposited adjacent to the Gabilian Range, which lies to the northwest on the opposite side of the fault, and that they subsequently have been displaced approximately 240 km (fig. 3.5).

The various aforementioned features that have been used to measure lateral offsets along the San Andreas fault are all situated near the present-day trace of the fault. They do not measure the substantial displacements that probably occurred along presently inactive older faults of the system, nor do they measure the large lateral movement (described below) that is thought to have occurred along the interface between continental and oceanic crust during the early plate-tectonic development of the fault system.

**RELATION OF GEOLOGIC STRUCTURE TO SEISMIC BEHAVIOR**

From the preceding descriptions, the San Andreas fault evidently cuts through many different types of rocks and regional structures along its traverse from the Transverse Ranges to the Mendocino triple junction, and the patterns of seismicity differ strikingly along various
segments of the fault. These differences in seismic behavior coincide so closely with certain geologic situations along the San Andreas fault in central California as to suggest a causal relation.

Certain segments of the San Andreas fault in central California are characterized by frequent small-magnitude earthquakes and aseismic slippage (creep); creep also occurs along the San Andreas fault in Coachella Valley, the Imperial fault, and the Superstition Hills fault. Other segments, said to be "locked," are characterized by infrequent earthquakes, some of which have been historically of large magnitude, and by an absence of creep. The occurrence of creep has been described by Allen (1968), Wallace (1970), Nason and Tocher (1970), and Thatcher (see chap. 7), among others. The creep is mainly on faults along the west side of the Diablo antiform. The creeping segment of the San Andreas fault extends from Cholame to near San Juan Bautista. Other faults known to creep include segments of the Calaveras, Hayward, Concord, Green Valley, and Sargent faults (fig. 3.7). The locked segments of the San Andreas fault in central California extend northward from near San Juan Bautista and southward from Cholame. Though of no recognized significance, the creeping segment of the San Andreas fault terminates near the north end of the Barrett Ridge slice of the Salinian block.

The creeping segments in central California occur where the faults regionally cut the upper plate of the Coast Range thrust (figs. 3.4, 3.7; Irwin and Barnes, 1975). This position accounts for the common presence of serpentinite along the creeping segments of the San Andreas fault, because the serpentinitiferous Coast Range ophiolite in the upper plate of the thrust is at the fault interface along these segments. The lower-plate Franciscan rocks form a geochemical province characterized by carbon dioxide-rich springs. Where the upper plate of the thrust is present, it may act as a hydraulic cap that helps to maintain high pore pressure caused by carbon dioxide in the underlying Franciscan rocks, and to direct fluid flow into the fault (Irwin and Barnes, 1975). The importance of pore pressure in relation to creep is its ability to reduce the frictional strength of rocks by lowering the effective confining pressure, as demonstrated by Byerlee and Brace (1972). The tectonic relations between carbon dioxide springs and seismicity were described by Irwin and Barnes (1980).

**Figure 3.6.** Idealized cross sections showing stratigraphic and lithologic similarity of the Neenach Volcanic Formation, on northeast side of the San Andreas fault in southern California, to lower half of northern part of the Pinnacles Volcanic Formation several kilometers west of fault in central California (modified from Matthews, 1975) (see fig. 3.5 for locations). agl, agglomerate; pr, porphyritic rhyolite.
SOUTHERN CALIFORNIA

TRANSVERSE RANGES AND THE SALTON TROUGH

Where the San Andreas fault bends eastward, near the south end of the Great Valley, it forms the boundary between the southern "tail" of the Sierra Nevada and rocks of the Transverse Ranges (fig. 3.3). Continuing southeastward along the Transverse Ranges, the fault trends along the north slope of the San Gabriel Mountains and the edge of the Mojave Desert for about 100 km, and then cuts diagonally between the San Gabriel and San Bernardino Mountains, where a major strand (San Jacinto fault) splits off to the south. The rocks traversed by the San Andreas fault in the Transverse Ranges are mainly Mesozoic plutons and their Precambrian metamorphic and plutonic host rocks.

South of the Transverse Ranges, the bedrock along the fault is concealed by Quaternary deposits of the Salton Trough for a length of more than 200 km. The Salton Trough, which includes the Coachella and Imperial Valleys, widens toward the southeast, and the number of faults and complexity of the zone increase. The east wall of the trough is at the San Andreas fault, where it consists of Precambrian rocks and Mesozoic plutons and of schists like those exposed in the Orocopia and Chocolate Mountains (fig. 3.8). The west wall consists of Cretaceous plutonic rocks of the Southern California batholith and their metamorphic host rocks, similar to rocks exposed in the nearby San Jacinto Mountains. As shown by Fuis and others (1982), the trough is a gap in the crystalline basement that is filled with Quaternary and older Cenozoic sedimentary rocks. The gap increases irregularly in width from 20 km at the north end of the Salton Sea to 60 km at the United States-Mexican border. The enormous thickness of the sedimentary fill is indicated by a drill hole that bottoms in Pleistocene (?) sedimentary rocks at a depth of about 4 km (Muller and Doe, 1966). Seismic-refraction studies show an interface with "basement" rocks at a depth of 5 to 6 km, and the "basement" rocks below the 5- to 6-km-deep interface are thought actually to be metamorphosed Cenozoic fill (Fuis and others, 1982). Near the south end of the Salton Sea, the San Andreas appears to terminate as a transform fault at a spreading center, or pullapart zone, that is the most northerly in a series of spreading centers distributed along the length of the Gulf of California which form part of the East Pacific Rift. The proximity of this pullapart zone accounts for the abundant young volcanic and geothermal features in the area (Elders and others, 1972).

The Precambrian rocks and associated Mesozoic plutons that constitute much of the crystalline basement cut by the San Andreas in southern California are locally seen to lie in thrust-fault contact on relatively younger metamorphic rocks. In the San Gabriel Mountains, on the southwest side of the San Andreas fault, the principal country rocks are divided into two plates by the Vincent thrust (lat 34°19' N., long 117°45' W.). As described by Ehlig (1981), the upper plate of this thrust is a Precambrian gneiss-amphibolite-granite complex (U-Pb age, approx 1,700 Ma; Silver, 1966) intruded by a Precambrian anorthosite-syenite-hedbro complex (U-Pb age, 1,220 Ma; Silver, 1971), all of which are intruded by the Late Triassic Lowe Granodiorite (U-Pb age, 220 Ma; Silver, 1971), by mid-Mesozoic rhyolitic to basaltic dikes, and, finally, by granitic plutons of probable Late Cretaceous age (U-Pb age, 80 Ma; Carter and Silver, 1971). The oldest rocks in the upper plate are thought to be a remnant of a Precambrian craton. Northeast of the fault, in the Mojave Desert and San Bernardino Mountains, some Precambrian rocks are unconformably overlain by lower Paleozoic mioecinal strata that are thought to represent an essentially autochthonous part of the North American craton (Burchfiel and Davis, 1981; Ehlig, 1981).

Figure 3.7.—Known creeping segments of the San Andreas and related faults in central and northern California. Data from Nason (1978), Frizzell and Brown (1976), Prescott and Burford (1976), Burford and Sharp (1982), and Harsh and Burford (1982). Faults: C, Calaveras; CD, Concord; GV, Green Valley; H, Hayward; RC, Rodgers Creek; S, Sargent. Compare creeping segments with concentrations of small earthquakes shown in figures 5.4 and 5.5.
The lower plate of the Vincent thrust consists of the Pelona Schist, which is largely a sedimentary section of arkosic sandstone, siltstone, and shale that has been metamorphosed to white mica-quartz-albite schist and locally includes metavolcanic rocks, metachert, marble, and serpentine (Ehlig, 1981). The section in the San Gabriel Mountains has an exposed thickness of 3.5 km. The metamorphism decreases downward, away from the fault, and so sedimentary structures, including graded bedding, are well preserved in the lowest 1 km of section. This “upside down” metamorphism and other features indicate that the metamorphism of the lower-plate rocks occurred during thrusting. Pelona-type schist also occurs beneath Precambrian rocks of the Barrett Ridge slice west of the Tejon Pass and crops out in places along the Garlock fault (fig. 3.9). On the northeast side of the San Andreas fault in the Orocopia-Chocolate Mountains area, just east of the Salton Sea, the schist, there known as the Orocopia Schist, lies below the Orocopia thrust. Scattered exposures of Pelona-type schist and the Vincent-Orocopia thrust continue into southwesternmost Arizona (Haxel and Dillon, 1978).

The protoliths of the Pelona-type schist are thought to be deep-marine sedimentary rocks deposited on oceanic crust, possibly representing mostly the distal parts of turbidite fans. They probably were Jurassic or Cretaceous in age and are thought to have been metamorphosed by the thrusting that probably occurred no later than Late Cretaceous time (Haxel and others, 1985). The tectonics of the Pelona and Orocopia Schists is controversial. The Vincent-Orocopia thrust may have dipped southwest, and the Precambrian and other rocks of the upper plate been thrust northeastward over backarc-basin protoliths of the Pelona and Orocopia Schists (Haxel and Dillon, 1978). Conversely, the thrust relation may represent a gently north-northeast dipping subduction zone in which the protoliths of the schists were trench deposits similar to the Franciscan rocks and were thrust north-northeastward under the sialic North American plate (Burchfiel and Davis, 1981; Crowell, 1981). The Pelona-type schist is reminiscent of the Franciscan-derived South Fork Mountain Schist and related semi-schists of northern California that form a narrow, virtually continuous selvage for hundreds of kilometers along the west edge of the Klamath Mountains and the west side of the Great Valley, where they form the lower plate of the Coast Range thrust (Blake and others, 1967).

**Figure 3.8.—Salton Trough and north end of the Gulf of California, showing major spreading centers and termination of the San Andreas fault (modified from Fuis and others, 1982). Spreading centers: BZ, Brawley seismic zone; CP, Cerro Prieto geothermal area; W, Wagner Basin. Major transform faults: CPF, Cerro Prieto; IF, Imperial; SAF, San Andreas. Other major faults: E, Elsinore; EH, East Highland Canal seismicity lineament; LS, Laguna Salada; SJ, San Jacinto.**

**EXPLANATION**

- **Spreading center**—Dashed where approximately located. Arrows show direction of spread
- **Inferred extent of Precambrian and related basement rocks**
- **Inferred extent of Southern California batholith and related basement rocks**
- **Submarine depression (Wagner basin)**
- **Approximate contact**—Queried where uncertain
- **Fault**—Dashed where approximately located; queried where uncertain. Arrows indicate direction of relative movement
- **Seismicity lineament**
The distribution of the Pelona-type schist (fig. 3.9) has played an important role in many attempts to measure the slip on the San Andreas fault in southern California. In their classic report, Hill and Dibblee (1953) recognized the similarity of the Pelona Schist of the San Gabriel Mountains area to the Orocopia Schist east of the Salton Sea and postulated that these schists are offset 257 km from one another by the San Andreas fault. Crowell (1962) noted that the Precambrian rocks and Pelona-type schist of the Tejon area are separated from those of the San Gabriel Mountains area by the San Gabriel fault and that the Tejon, San Gabriel Mountains (Soledad), and Orocopia Mountains areas contain not only similar Precambrian rocks and Pelona-type schist but also similar Oligocene and other Tertiary strata. The similar lithologies and geologic histories of the rocks of these three areas indicated to him that these rocks once formed an east-west-trending belt which has been segmented and displaced by right-lateral slip of approximately 50 km on the San Gabriel fault and 210 km on the San Andreas fault. However, the validity of the concept that the Tertiary rocks of the San Gabriel (Soledad) and Orocopia Mountains areas once were parts of a single basin was questioned by Spittler and Arthur (1973), who believed that the Tertiary strata of these two areas were deposited in separate basins, consist of distinctly different flow rocks, and are dissimilar in age.

More recent schemes for measuring offset along the San Andreas fault in southern California have been proposed. Among them, Powell (1981) postulated that all major exposures of the Pelona-type schist are in the core of an antiformal fold and that they once formed a nearly continuous structure which subsequently has been disrupted by Cenozoic strike-slip faults (fig. 3.10). An important part of Powell’s palinspastic reconstruction of the antiform is an old east-west-trending fault that is a composite of the San Francisquito, Penner, and Clemens Well faults. This fault is thought to have had 80 km of right-lateral slip, cutting the antiform, and later was cut diagonally by the San Andreas fault. The axis of the antiform structure is a linear feature that can be used as a “piercing point” in measuring offset where the axis appears on opposite sides of a fault. On this basis, the axis of the San Gabriel Mountains (Sierra Pelona) area is offset 220 km along the San Andreas fault from the axis in the Orocopia Mountains area (Powell, 1981). The Transverse Ranges segment of the San Andreas fault was described by Matti and others (1985) as consisting of several old strands (Wilson Creek, Mission Creek, and

![Figure 3.9](image-url)  
**Figure 3.9.** Distribution of the Pelona Schist and lithologically similar schists in southern California and southwestern Arizona (modified from Hazel and Dillon, 1978). Northernmost occurrence along the San Andreas fault is in Barrett Ridge slice of the Salinian block.
Mill Creek faults) and a young strand (San Bernardino strand). The total displacement across all of these strands is thought to be 160±10 km (Matti and others, 1986), on the basis of exposures of a distinctive Triassic megaphyllic monzogranite. The exposures of this monzogranite, which are on the northeast side of the San Andreas fault in the San Bernardino Mountains but on the opposite side of the fault in Liebre Mountain (at 34°43′ N., long 115°40′ W.), are thought to represent displaced parts of the same pluton.

PLATE-TECTONIC DEVELOPMENT OF THE SAN ANDREAS FAULT

The Pacific coast of North America is a highly mobile zone of tectonic interaction between continental crust on the east and oceanic crust on the west. At some times and places, the relative movements of these contrasting crustal domains have been sufficiently convergent that the oceanic crust has underthrust the continental crust and swept island arcs and other crustal materials into the zone of interaction (Hamilton, 1969). However, much of the movement along this zone of interaction seems to have been oblique or lateral in an overall northwest-southeast direction, and so as the two types of crust moved past one another, fragments of all sizes were sliced or pulled from them and carried various distances away from their source. By these processes of convergence and lateral translation, large crustal fragments referred to as "terranes" (Irwin, 1972; Coney and others, 1980; Schermer and others, 1984) are juxtaposed against others that may differ strikingly in lithology, age, genetic environment, stratigraphy, metamorphic facies, plutomism, and mineral deposits.

The general directions and rates of movement of the major crustal domains that converged along the western margin of North America are amenable to explanation by the theory of global plate tectonics as far back in time to

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**EXPLANATION**

- Antiform
- Fault—Dashed where approximately located; queried where uncertain

**Figure 3.10.**—Sequential diagrams showing evolution of the San Andreas fault system in southern California as proposed by Powell (1981). A, Approximately 30–15 Ma—formation of regional antiform core by schist lithologically similar to the Pelona Schist. B, Approximately 20–10 Ma—displacement of antiform by the San Francisco-Fenner-Clemons Well fault. C, Approximately 10–2 Ma—inception of San Andreas-San Gabriel strand of the San Andreas fault, displaying approximately 60 km of right-lateral displacement. D, Approximately 5–0 Ma—left-lateral bending of San Gabriel segment and possible inception of the Garlock fault. E, Approximately 2–0 Ma—inception of modern southern-California segment of the San Andreas fault, displaying 220 km of right-lateral displacement. F, Approximately 2–0 Ma—left-lateral bending of Transverse Ranges segment of the San Andreas fault and development of the San Jacinto fault. Faults: CW, Clemens Well; F, Fenner; SA, San Andreas; SF, San Franciscoito; SG, San Gabriel. Antiform segments: CM, Chocolate Mountains; ESG, Eastern San Gabriel Mountains; LSB, Little San Bernardino Mountains; O, Orocopia Mountains; SP, Sierra Pelona; SS, Sierra de Salinas.
at least the Mesozoic (Engebretson and others, 1985). According to this theory, the crust of Earth is a mosaic of interacting rigid plates. Boundaries between the plates are spreading ridges where the plates pull apart, oceanic trenches above subduction zones where the plates converge, and transform faults where the plates slide laterally past one another. These boundaries are the loci of seismic activity. The corollaries of the theory of global plate tectonics have been enormously valuable as an aid in recognizing the genetic environments of the various terranes, whether oceanic or continental crust, volcanic island arc, or oceanic trench. The presence of multiple ophiolite and blueschist belts along parts of the western margin of North America (Irwin, 1977) indicates that some of these terranes were subduction related during Paleozoic and Mesozoic time. Although much has been learned of the relative motions between the oceanic and continental rocks for the past 180 m.y. (for example, Engebretson and others, 1985), the tectonics of the zone of allochthonous terranes is so complex, and the sites of origin of the various terranes generally so obscure, that much painstaking research remains to be done before the Paleozoic and Mesozoic margins of western North America can be painstakingly reassembled.

The tectonic setting of the continental margin during late Mesozoic time, before development of the San Andreas fault, is highly controversial. Some geologists (for example Dickinson, 1981) favor a model of highly convergent plate interaction to develop a continental margin of the Andean type (fig. 3.11). Others, however, interpret certain paleontologic and paleomagnetic evidence to indicate that some late Mesozoic rocks of the Coast Ranges were translated great distances northward from equatorial sites of origin during Late Jurassic time, before accretion to North America and deposition of the Great Valley sequence (Hopson and others, 1986). This movement is thought to have been followed in Late Cretaceous and early Tertiary time by a second episode of dextral translation during which part of the Franciscan assemblage was accreted and parts of the Coast Range ophiolite and overlying Great Valley sequence moved northward for distances as great as 1,120 km (McLaughlin and others, 1988).

The rates and relative directions of motion of the principal tectonic plates are based mainly on patterns of magnetic anomalies in the oceanic crust. These patterns indicate that a subduction-related trench lay offshore of western North America during early Tertiary time because of the convergence of the Farallon plate (see fig. 3.1), and that strike-slip movement on faults of the San Andreas system began no earlier than approximately 30 Ma (late Oligocene), when the Pacific plate first impinged on the North American plate (McKenzie and Morgan, 1969; Atwater, 1970). Triple junctions formed at the point of contact of the Pacific plate with the North American plate and migrated to the northwest and southeast as subduction of the Farallon plate continued. These triple junctions are now approximately 2,500 km apart: The Mendocino triple junction is off the coast of northern California, and the Rivera triple junction is at the mouth of the Gulf of California. The relative motion along the transform fault that formed the lengthening boundary between the Pacific and North American plates was right lateral. This early transform movement probably was not along the modern trace of the San Andreas fault but must have been along other faults of the system that now lie mostly to the west and at the edge of the continent (fig. 3.12). The modern San Andreas fault apparently did not come into being in southern California until the opening of the Gulf of California during Pliocene time, about 4 Ma, since which time Baja California has moved 260 km away from mainland Mexico (Larson and others, 1968). The San Andreas fault is commonly referred to as the boundary between the Pacific and North American plates, which is true in the sense that the rocks on the west side of the fault are moving somewhat in concert with the Pacific plate, although those rocks actually are displaced fragments that once were part of the North American plate (fig. 3.13).

During the early development of the San Andreas fault system, the principal movement must have been along a transform fault that formed the boundary between rocks of the North American plate and newly formed oceanic crust of the Pacific plate as the triple junction migrated southward. At some point during southward migration of this triple junction, the transform apparently jumped eastward one or more times to positions within the North American plate, to become the northern section of the modern San Andreas fault. The modern trace of the San Andreas fault in central California probably had only minor slip until about 12.5–10 Ma and probably was not

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**Figure 3.11.**—Schematic diagram showing California as an Andean-type continental margin during late Mesozoic time (modified from Dickinson, 1981).
Figure 3.12.—Sequential diagrams showing plate-tectonic evolution of the San Andreas transform fault system (modified from Dickinson, 1981). Note that early transform faulting was west of the present-day San Andreas fault and presumably separated young oceanic rocks of the Pacific plate from rocks of the North American plate. Over time, the transform faulting has stepped eastward, and so virtually all the presently most active element, the present-day San Andreas fault, is now in rocks of North American plate aspect. In earlier diagrams, partial outline of the Gulf of California, which did not exist before 5 Ma, is shown for reference only.
the strand of dominant slip before 7.5–5 Ma (Dickinson and Snyder, 1979). The southern section of the modern San Andreas fault was formed by similar eastward jumps of the transform fault, resulting in opening of the Gulf of

EXPLANATION

- North American plate
- Captured part of North American plate
- Remnants of Farallon plate
- Pacific plate

- Spreading center—Arrows indicate direction of spreading
- Fault or fracture zone—Arrows indicate direction of relative movement
California. Some of the major faults that lie between the San Andreas fault and the continental margin may represent these earlier positions of the transform, and some of these faults are still active. Possible candidates for such early intermediate faults include, among others, the San Gregorio-Hosgri fault in central and northern California and the Elsinore and offshore faults in southern California. With our present state of knowledge, however, it is unclear which of the many faults in the Coast Ranges are early faults of the San Andreas system and which may have formed before mid-Tertiary initiation of the San Andreas system.

The models of McKenzie and Morgan (1969) and Atwater (1970) have been widely used in relating Pacific plate interactions to the tectonics and geology of California and other parts of western North America (fig. 3.1). A more analytical developmental sequence of diagrams was drawn by Dickinson (1981), in which the position of an early San Andreas fault is shown before the opening of the Gulf of California (fig. 3.12). In figures 3.1 and 3.12, the boundary between the Pacific and North American plates is shown as a transform fault that was formed by the passage of migrating triple junctions. However, marine geologic studies offshore of California between Point Conception and Cape Mendocino indicate that this old interface between the Pacific and North American plates is an inactive east-dipping low-angle fault which is interpreted to be a fossil subduction zone (McCulloch, 1987). There, magnetic stripes of the oceanic (Pacific) plate can be traced some distance eastward—locally as much as 30 km—beneath the leading edge of the upper (North American) plate, and both plates are covered along the suture by a thin veneer of undeformed Miocene strata. The presence of a Miocene or older subduction zone rather than a transform fault at the ocean-continent interface is difficult to reconcile with a strict interpretation of McKenzie and Morgan’s (1969) and related models, although it is interpreted to indicate that the transform motion was accompanied by oblique convergence (McCulloch, 1987).

The present overall rate of relative movement between the Pacific and North American plates, earlier thought to be about 6 cm/yr (Atwater, 1970) or 5.6 cm/yr (Minster and Jordan, 1978), is now thought to be more likely about 4.8 cm/yr (DeMets and others, 1987). This rate has varied over time (Atwater and Molnar, 1973); however, the rate of relative motion between the two plates is substantially greater than the slip rates based on measured offsets of geologic features along the San Andreas fault. For example, the 315-km offset of the lower Miocene Pinnacles and Neenach Volcanic Formations indicates a minimum overall slip rate of 1.3 to 1.4 cm/yr (Matthews, 1976), and the offset of the channel of Wallace Creek by the San Andreas fault in central California indicates a slip rate of about 3.4 cm/yr for the past 3,700 yr and of 3.6 cm/yr for the past 13,250 yr (Sieh and Jahns, 1984). Geodetic-survey measurements indicate that slip rates during the past 90 yr in central California average 2.9 cm/yr for the upper 15 km of crust but 3.7 cm/yr below 15 km (Thatcher, 1977). The discrepancy between the rate of relative motion between the Pacific and North American plates and the much smaller slip rate on the San Andreas fault has been noted by many workers (for example, Atwater, 1970; Minster and Jordan, 1978; Weldon and Humphreys, 1986). Part of the total slip along the boundary between the Pacific and North American plates probably is occurring in small increments along other faults in a broad zone of interaction that may extend from the continental margin eastward even as far as the Basin and Range province.

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