SAN ANDREAS FAULT IN THE CALIFORNIA COAST RANGES PROVINCE

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The San Andreas fault (p. 355) is California's most spectacular and widely known structural feature. Few specific geologic features on earth have received more public attention. Sound reasons for this are found in the series of historic earthquakes which have originated in movements in the San Andreas fault zone, and in continuing surface displacements, both accompanied and unaccompanied by earthquakes. This active fault is of tremendous engineering significance, for no engineering structure can cross it without jeopardy, and all major structures within its potential area of seismicity must incorporate aseismic design features. Recently a proposal for a great nuclear power plant installation on Bodega Head, north of San Francisco, was abandoned because of public controversy over the dangers of renewed movements and earthquakes on the nearby fault (Koenig, 1963; and fig. 1, photo 1). Expensive design features are being incorporated into the State's plan to transport some of northern California's excess of water to water-deficient southern California in order to ensure uninterrupted service across the fault in the event of fault movements and earthquakes in the Tehachapi area (James, 1964).

Worldwide attention of geologists and seismologists to the San Andreas fault has resulted from: (1) the great ($M = 8.25$) San Francisco earthquake of 1906 (Lawson and others, 1908) and many lesser shocks which have originated in the fault zone, (2) development of the "elastic rebound" theory by H. F. Reid in the Lawson report, (3) striking geologic effects of former and continuing surface movements in the fault zone, and (4) postulated gigantic right-slip displacement (Hill and Dibblee, 1953). The San Andreas has been frequently and widely cited in the scientific and popular literature as a classic example of a strike-slip fault with cumulative horizontal displacement of several hundred miles; this in spite of the highly controversial nature of the geologic evidence that can be documented!

LOCATION AND EXTENT

The San Andreas fault strikes approximately N. 35° W. in a nearly straight line in the Coast Ranges province and extends southward for a total length of about 650 miles from Shelter Cove in Humboldt County to the Salton Sea. This carries it at a low angle completely across structures and lineation of the Coast Ranges, south across the Transverse Ranges, and into the Salton Trough. Latest movement in the fault zone, as noted by Lawson and others (1908) who named and traced it, has thus been clearly later than all major structural features of those provinces. This recent movement may, however, be an expression of renewed activity along an older fault zone that antedated differentiation of the geologic provinces now in existence. If so, we need to distinguish between the ancestral "San Andreas" fault zone and the Quaternary San Andreas fault proper (pl. 1, Geologic map of California).

The long northwesterly trend of the fault zone is interrupted in three places (pl. 1): (1) At Cape Mendocino, where it turns abruptly westward to enter the Mendocino fault zone, as reflected in the Mendocino Escarpment, or is offset left laterally and continues northwestward from that escarpment; (2) at the south end where the Coast Ranges adjoin the Transverse Ranges and the fault turns to strike east into the complex knot of major faults in the Frazier Mountain area and on emerging splits into the 50-mile-wide system of related faults, including the San Andreas fault proper, in southern California; and (3) in the San Gorgonio Pass area where the San Andreas fault proper appears to change direction again and butt into the Mission Creek-Banning fault zone which continues into the Salton Trough. That these three changes in trend are of profound structural significance, most geologists would agree, but there is wide disagreement on possible explanations.

HISTORY OF GEOLOGICAL INVESTIGATIONS

A. C. Lawson (1893) first recognized faulting in the San Andreas fault zone when he said "The line of demarcation between the Pliocene and the Mesozoic rocks, which extends from Mussel Rock southeastward is, in part, also, the trace of a post-Pliocene fault." In 1899, F. M. Anderson recognized evidence of major faulting on the Marin peninsula "both in the topography and in the general stratigraphic and petrographic relations". However, he projected this fault southeastward into Lawson's fault along the western margin of San Bruno Mountain, rather than connecting it with the major "post-Pliocene" fault mentioned by Lawson. Neither of these two geologists gave a name, at that time, to the San Andreas fault.

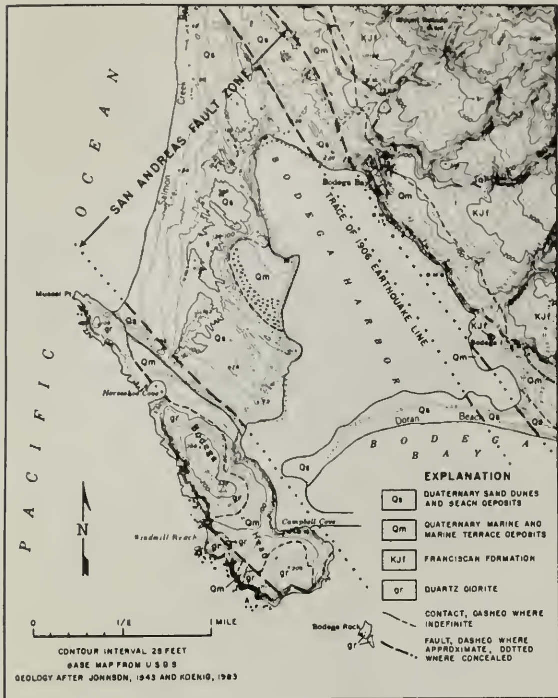

Figure 1. Geologic map of San Andreas fault zone at Bodega Head. *From California Div. Mines and Geology Mineral Inf. Service, v. 16, no. 7, 1963.*

The great San Francisco earthquake of 1906 and the obvious surface rupture focused attention of leading California geologists of the day on the fault, and resulted in publication of the monumental report of the State Earthquake Investigation Commission (Lawson, 1908). Lawson was assisted by many American geologists, prominent then or later, including Robert Anderson, J. C. Branner, A. S. Eakle, H. W. Fairbanks, G. K. Gilbert, F. E. Matthes, G. D. Louderback, and G. A. Waring. They described surface fault ruptures from Shelter Cove in Humboldt County to San Juan Bautista in San Benito County, a distance of approximately 250 miles, but they also followed the Recent fault into San Bernardino County. In this report Lawson first named the San Andreas fault after its rift-valley expression in the San Andreas Lake area of the San Francisco peninsula.

In volume II of the Earthquake Commission Report, not published until 1910, H. F. Reid developed his "elastic rebound theory" to account for the origin of earthquakes. This report contains a number of seismograms and isoseismal maps. This volume, like volume I, is abundantly illustrated and is a fascinating geologic document.

Other significant outgrowths of the 1906 earthquake were the founding of the Seismological Society of America, the publication of the first Bulletin of the Society in 1911, and the installation of new seismographs by the University of California at Berkeley and at Lick Observatory in 1910.

In 1914 the U.S. Geological Survey published the San Francisco Folio by Lawson, still a standard reference for geology of the Bay area, although long since out of print.

During the past 25 years many geologic maps have been published of parts of the Coast Ranges which include segments of the San Andreas fault zone, and more mapping is in progress. A complete list of these through 1960 has been published in Special Reports 52 and 52A by the California Division of Mines and Geology (Strand, Koenig and Jennings, 1958; Koenig, 1962). Their 1:250,000-scale sheets of the State Geologic Map that include both published and unpublished geologic mapping across the San Andreas fault zone in the Coast Ranges province are: Redding (1962), Ukiah (1960), Santa Rosa (1963), San Francisco (1961), San Jose (in press 1966), Santa Cruz (1959), San Luis Obispo (1959), and Bakersfield (1965).

Oakeshott (1959) in a report on the *San Francisco earthquake of March 1957* included summary papers by various authors on the geology, seismic history, and structural damage of a Bay area segment of the

Photo 1. Aerial view of Bodega Head, looking northward, with village of Bodega Bay at center of the photograph. The steep cliffs at the bottom of the picture reach a height of about 170 feet. Sandy beach in the middle ground, connecting Bodega Head to the mainland, corresponds to the seismically active San Andreas fault zone. *From California Div. Mines and Geology Mineral Inf. Service, v. 16, no. 7, 1963. Photo by Aero Photographers, Sausalito, California.*

San Andreas fault zone. Special Report 74 (Jennings and Strand, 1963) of the Division of Mines and Geology lists graduate theses on California geology. The latest listing of current research projects by colleges and universities on subjects pertaining to California geology, including some which have direct bearing on San Andreas fault problems is in the July 1964 issue of the Division's *Mineral Information Service* (Campbell and Jennings, 1964).

In December 1964, The Resources Agency, State of California, held a public scientific conference on earthquake hazards (California Resources Agency, 1964), and this agency, through its Division of Mines and Geology and Department of Water Resources, has embarked on a long-range program of fault and earthquake investigations, particularly emphasizing the San Andreas fault. In May 1965, The Resources Agency held a second geologic hazards conference in which the emphasis was placed on landslides and subsidence (California Resources Agency, in press, November 1965). At the time this report was being prepared (November 1, 1965), announcements were being made of several long-range, far-reaching programs designed to learn more of the San Andreas fault, in particular, and of faulting and earthquakes in general. A recent summary of earthquake investigations in progress, and planned, in California may be found in the California Resources Agency publication (1964) just cited.

The University of California Seismograph Station has received approval of the Regents to start construction of a multipurpose geophysical observatory to be located in granitic rock just west of an active segment of the San Andreas fault a few miles south of Hollister. This installation will provide instrumentation for long-term recording of elastic and acoustic waves, tilt, strain, and conductivity fluctuations as well as varia-

Photo 2. San Andreas(?) fault scarp at Shelter Cove in Humboldt County, photographed in 1963. East side (left) is up about 6 feet. Cut at base of scarp was made for a road. *Photo by K. V. Steinbrugge*

tions in the magnetic, gravity, and heat fields near the fault.

The U.S. Coast and Geodetic Survey is continuing and increasing its long-time program of strong motion studies and resurveys across the fault zone (Meade and Small, this bulletin).

The U.S. Geological Survey, in July 1965, began accelerating its geologic and geophysical analysis of the western earthquake belt, particularly along the San Andreas fault zone. Geologic investigations included geomorphic studies of Quaternary displacements, analyzing the development and offset of Tertiary basins, and offsets of granitic, metamorphic, and volcanic blocks and gravels derived therefrom. Geologic maps and sections representing transects of the fault and a synthesis of the regional tectonics were being prepared at scales of 1:62,500 and 1:125,000. A variety of geophysical studies including emphasis on seismic-refraction profiling and study of near earthquakes, and studies of tilt-measuring, strain seismometry, and electronic distance measurement among other techniques were begun in and near the fault zone. In October 1965, the U.S. Department of the Interior announced establishment of a National Center for Earthquake Research within the Geological Survey to stimulate and coordinate research on the causes and prediction of earthquakes.

By an understanding in effect for many years, earthquakes north of the Kern County line have been studied particularly by the University of California Seismograph Station, while those originating in Kern County and south have been the prime responsibility of the Seismological Laboratory of the California Institute of Technology.

EARTHQUAKE HISTORY

Earthquake history of California is extremely short. The earliest earthquake in written records was felt by explorer Gaspar de Portolá and his party in 1769 while camped on the Santa Ana River about 30 miles southeast of Los Angeles. The earliest seismographs in use in California, and also the earliest in the United States (Louderback, 1942), were installed by the University of California at Lick Observatory on Mount Hamilton, and at the University at Berkeley in 1887. Earliest seismograms of a major California earthquake are those of the San Francisco earthquake of 1906, which was recorded at seven California stations as well as elsewhere throughout the world. Townley and Allen (1939) is the standard reference on earthquakes prior to 1929. Byerly (1951), VanderHoof (1955), Richter (1958), and Tocher (1959) have published accounts of earthquakes in the Coast Ranges.

One of the Bay area's largest earthquakes centered on the Hayward fault (within the San Andreas fault zone) in the East Bay on June 10, 1836. Surface faulting took place at the base of the Berkeley Hills from Mission San José to San Pablo. On October 21, 1868, another large earthquake centered on the Hayward fault with surface faulting for about 20 miles from Warm Springs to San Leandro (Radbruch, 1965). Maximum right-lateral offset was about 3 feet.

In June of 1838 a strong earthquake originating on the San Andreas fault was accompanied by surface rupturing from Santa Clara almost to San Francisco.

This damaged the Presidio at San Francisco and the missions at San Jose, Santa Clara, and San Francisco. Another strong earthquake centered on the San Andreas fault in the Santa Cruz Mountains on October 8, 1865. This was accompanied by ground cracks, landslides and dust clouds; buildings were damaged in San Francisco and at the New Almaden mercury mine, which was only a few miles east of the active part of the fault.

On April 24, 1890, a strong earthquake damaged Watsonville, Hollister, and Gilroy. Mr. Joe Anzar, who was a young boy living in the San Andreas rift valley in the nearby Chittenden Pass area at the time of that earthquake, was interviewed in 1963 by Olaf P. Jenkins and Oakeshott. Anzar clearly remembered ground breakage, which caused Anzar Lake to drain, and landslides, which closed the railroad and highway where the fault trace crosses Chittenden Pass. He judged the motion to be stronger (at his home) than during the San Francisco earthquake of 1906.

The famous San Francisco earthquake, 5:12 a.m. local time, April 18, 1906, was probably California's greatest. Visible surface faulting occurred from San Juan Bautista to Point Arena, where the San Andreas fault enters the ocean. At the same time surface faulting also occurred 75 miles north of Point Arena at Shelter Cove in Humboldt County, but it is not certain whether this was along the San Andreas fault proper or whether the breakage took place on an *en echelon* fault in the same zone. The 1906 scarp viewed at Shelter Cove in 1963 (photo 3, 4) clearly shows upthrow of 6 to 8 feet on the east side; there was no evidence of a horizontal component of displacement. However, offset of a line of old trees and an old fence viewed east of Point Arena in 1963 gave clear evidence of right-lateral displacement on the order of about 14 feet. The epicenter of the earthquake was near Olema, at the south end of Tomales Bay, near where a road was offset 20 feet in a right-lateral sense. Richter magnitude is generally computed at about 8.25. Damage has been estimated at from $350 million to $1 billion. An estimated 700 people were killed. A large part of the loss was due to the tremendous fires in San Francisco, which resulted from broken gas mains and lack of water owing to numerous ruptures in the lines.

Another of California's great earthquakes, comparable in magnitude to the San Francisco 1906 earthquake, was caused by displacement on a segment of the San Andreas fault extending through the southern part of the Coast Ranges province and on beyond across the Transverse Ranges. This Fort Tejon earthquake of January 9, 1857, probably centered in the region between Fort Tejon in the Tehachapi Mountains and the Carrizo Plain in the southern Coast Ranges. Surface faulting extended for 200 to 275 miles from Cholame Valley along the northeast side of the Carrizo Plain through Tejon Pass, Elizabeth Lake, Cajon Pass and along the south side of the San Bernardino Mountains. Accounts of this earthquake are unsatisfactory and inconclusive, but surface displacement almost certainly amounted to several feet in a right-lateral sense (Lawson and others, 1908; Townley and Allen, 1939; Wood, 1955).

Photo 3. Sag pond and notched ridge in zone of 1906 fault ruptures at Shelter Cove, photographed looking south in 1963. *Photo by K. V. Steinbrugge.*

Photo 4. Aerial view of San Andreas fault in the northern Temblor Range, looking toward the north. Long narrow valley toward upper right is Antelope Valley. The fault trace here lies within gravels and sands of the Plio-Pleistocene Paso Robles Formation. *John S. Shelton photo.*

Thus, there have been in historic times two great earthquakes originating on the San Andreas fault, each accompanied by over 200 miles of surface ruptures: one at the southern end of the Coast Ranges and one in the north. Between is left a segment, roughly 90 miles long, in the southern Coast Ranges, which has not been disrupted by surface faulting in historic time. It is interesting to note that the two ends of this segment—the Hollister area and the Parkfield area—are now the most seismically active in the southern Coast Ranges. The extreme southern segment—south of the Tehachapi Mountains—is quiet on the San Andreas fault proper, but very active on the closely related San Jacinto, Elsinore, Inglewood, and Imperial faults (Allen and others, 1965). In the segment of surface rupture in 1906 many earthquakes have originated in the central and southern part of the San Andreas fault and its auxiliary faults in the East Bay—the Hayward and Calaveras faults. However, since 1906 there have been no earthquakes on the most northerly segment from Marin to Humboldt Counties (Tocher, 1959). The strongest earthquake in the Bay area since 1906 was the San Francisco earthquake of March 22, 1957, of magnitude 5.3. It originated at shallow depth near Mussel Rock, off the coast a few miles south of San Francisco; there was no surface faulting.

GEOMORPHIC FEATURES

Extensive activity along the San Andreas fault zone in Quaternary time has developed a linear depression, marked by all the features of a classic rift valley, extending the entire length of the fault and encompassing a width from a few hundred feet to over a mile and a half. Rift-valley features are particularly well expressed in the San Francisco Bay area (Oakeshott, 1959). Within the rift zone always occurs fault gouge and breccia and a disorganized jumble of fault-brecciated rocks of both the eastern and western blocks, the result of hundreds of repeated ruptures on different fault planes in late Pleistocene and Recent time. Features of the rift valleys have resulted from: (1) Repeated, discontinuous fault ruptures on the surface, often with the development of minor graben, horsts, and pressure ridges; (2) landsliding, triggered by earthquake waves and surface faulting; and (3) erosion of brecciated, readily weathered rock. Within the rift-valley troughs, it is common to find late Pliocene to Recent sediments.

Many of the observations made after the earthquake of 1906 are of great significance in understanding the origin and development of rift valleys and the nature of movement on the San Andreas fault: (1) Open ruptures were mapped along the fault trace from San Juan Bautista to Point Arena, and at Telegraph Hill north of Shelter Cove in Humboldt County; (2) individual fault ruptures were not continuous, but extended for a few feet to a mile or a little more, with the continuations of the displacements being picked up along *en echelon* breaks; (3) the ruptures were often complex, with small grabens and horsts developed between breaks; (4) apparent movements were dominantly right lateral, with lesser vertical displacements; and (5) the amount of displacement varied irregularly along the fault trace, but in a gross way decreased in both directions from the maximum at the south end of Tomales Bay.

North of San Francisco, across Marin County, the fault follows a remarkably straight course approximately N. 35° W. The most prominent features are Bolinas Bay and the long, linear Tomales Bay which lie in portions of the rift valley drowned by rising sea waters following the Pleistocene glacial epoch. Between these bays, the rift zone is a steep-sided trough, in places as deep as 1,500 feet, with its lower levels characterized by a remarkable succession of minor, alternating ridges and gullies parallel to the general trend of the fault zone. Surfaces of the ridges and gullies are spotted by irregular hummocks and hollows; many of the hollows are undrained and have developed sag ponds, so common along the San Andreas rift. Geologically Recent adjustment of the drainage in the rift zone leaves little positive evidence of the amount and direction of Recent displacement, except for that which took place in 1906. Offset lines of trees in this area still show the 13- to 14-foot right slip of 1906, and just south of Point Arena they also serve to show the 1906 offset. A large-scale plane-table map of the Fort Ross region by Matthes, published in the Earthquake Commission report (Lawson and others, 1908), is the best record of that portion of the rift zone in 1906. In the long stretch northward from Fort Ross to a point a few miles south of Point Arena, the broad expression of the rift zone is clear, but minor features within the zone have been obscured by erosion of the Gualala and Garcia Rivers and by the dense forest cover of the area.

South of San Francisco across San Mateo County the San Andreas fault zone follows the same trend as to the north but is less straight and is complicated by several subparallel faults. Near Mussel Rock, where the fault enters the land south of San Francisco, are great landslides which obscure the trace, and for a few miles to the southeast is a succession of sag ponds, notched ridges, and rift-valley lakes within a deeply trenched valley. The long, narrow San Andreas Lake and Crystal Springs Lakes are natural lakes which were enlarged many years ago by the artificial dams built to impound San Francisco's water supply. Similar rift-valley features mark the fault southward to the Tehachapi Mountains; because of the local aridity, they are particularly clear and striking in the Temblor Range area, in the Cholame Valley, and in the Carrizo Plain (photo 5, fig. 2). As the fault enters its eastward bend in the San Emigdio Mountains area, the rift-valley features become less striking, perhaps because the contrast between the basement rocks in the east and west blocks disappears where the fault lies wholly within granitic rocks and older schists (Crowell and others, 1964).

STRATIGRAPHY ALONG THE FAULT ZONE NORTH OF THE TEHACHAPI MOUNTAINS

The Coast Ranges province is a series of north-northwest-trending mountain ranges and intermontane valleys bounded on the east by the Great Valley and on the west by the Pacific Ocean. Since the San Andreas fault trends slightly more to the west than the general trend of the province, the fault zone completely crosses the Coast Ranges from its suboceanic junction with the Mendocino Escarpment on the north to the foothills on the western margin of the San Joaquin Valley in the south. The fault zone therefore crosses all essential elements of the extremely complex geology of the Coast Ranges. This geology has been treated earlier in this bulletin by Ben M. Page; I wish only to emphasize here those features which seem to have the greatest bearing on geologic history of the great San Andreas fault.

Perhaps the most geologically significant feature of the San Andreas fault in the Coast Ranges is that it separates two regions containing entirely different "basement" rocks—the Sur Series and quartz diorite to the west, and the Late Jurassic to Late Cretaceous Franciscan Formation to the east. There are apparent exceptions to this. It is unknown whether the fault under the ocean north of Point Arena continues to mark such a separation; the short segment on which surface displacement took place near Shelter Cove, in south coastal Humboldt County, in 1906 appears to lie wholly within Franciscan-type rocks. It may well be, however, that the Humboldt County fault is an *en echelon* fault within the San Andreas zone, and is not on the fault trace proper. On the San Francisco peninsula, the active San Andreas fault also lies wholly within the Franciscan Formation for a few miles where

Photo 5. Aerial view of San Andreas fault on the east side of Carrizo Plain, looking east. This area is about 35 miles south of that shown in figure 5. Note that at least three *en echelon* fault traces are visible here. The youngest trace is that out on the valley floor, and as it is the only one which has offset modern drainage, it may be part of the surface fault associated with the 1857 Fort Tejon earthquake. Here the youngest fault trace appears to be the contact between valley alluvium and the Paso Robles Formation.

the older, inactive Pilarcitos fault forms the major rock-province contact. At the southern end of the Coast Ranges, where the San Andreas fault begins its sharp bend to enter the Transverse Ranges province, the fault is wholly within Late Mesozoic granitic rocks that appear to be continuous from the Sierra Nevada around the southern end of the San Joaquin Valley into the Coast Ranges. Farther south, the San Andreas fault is entirely within the "granitic" province. Any hope of unraveling pre-Tertiary history of the fault lies in understanding the origin, age, and geologic history of the two great lithologic units it separates. Herein lie serious difficulties.

Franciscan Formation

The Franciscan Formation is a heterogeneous unit of eugeosynclinal marine sedimentary and volcanic rocks which consists predominantly of massively bedded graywacke with interbedded dark shale, minor amounts of chert and limestone, altered volcanic rock (greenstone), and various metamorphic rocks of the zeolite, blueschist, greenschist, and eclogite facies. These rocks have been intruded by sill-like masses of peridotite, mostly serpentinized, which are prevalent in some parts of the San Andreas and related fault zones. The serpentine is highly mobile and much of it appears as "cold intrusions." A comprehensive paper by Bailey, Irwin, and Jones (1964) summarizes knowledge of the Franciscan and adds much new material based on modern geologic mapping and laboratory research. Rocks of the Franciscan Formation crop out very widely in all parts of the Coast Ranges, except between the San Andreas and Nacimiento fault zones. The formation is perhaps as much as 50,000 feet thick, but no top or base has been observed; the sediments and volcanics were probably deposited on ultramafic

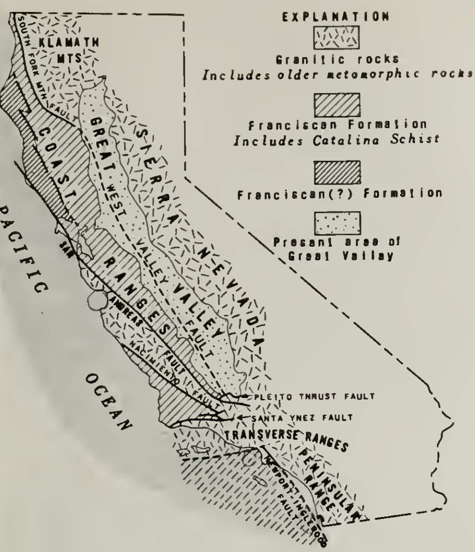

Figure 2. Franciscan-granite contacts, with shelf-facies rocks of Late Jurassic and younger age removed. Three great fault zones—Nacimiento, San Andreas, South Fork Mountain-West Valley—separate Franciscan "basement" rocks from granitic rocks (including older schists and gneisses and some unmetamorphosed rocks).

materials of the upper mantle (peridotite and serpentine), or on the "oceanic" layer, in deep, narrow, geosynclinal troughs by slides and turbidity currents, at the foot of the continental slope.

The large area shown on the Santa Rosa sheet of the State Geologic Map as "undivided Cretaceous marine" rocks in the coastal belt extending from Fort Ross to Point Arena, entirely east of the San Andreas fault, will be regarded here, as it was by Bailey and others, as a volcanic-poor unit of the Franciscan Formation of Cretaceous age. Fossils are very scarce throughout the entire Franciscan Formation, but the age range seems to be from Late Jurassic to Late Cretaceous. In any one area it is usually either Late Jurassic *or* Late Cretaceous. The older unit appears to be east of the Hayward fault and its northward projection.

Based on considerations of the pressure-temperature conditions of formation of the blueschists, Bailey and others postulate the metamorphic rocks indicate temperatures of less than 300°C, but pressures of 5 or more kilobars. They believe that these rocks must therefore have reached a depth of something like 70,000 feet, through accumulation and downwarping, so rapidly that a normal thermal gradient was not established. Uplift must have been equally rapid. If this sort of reasoning is valid, then "absolute" uplift of the Franciscan Formation on the San Andreas fault may have been on the order of 13 miles, perhaps beginning at the close of the Jurassic. Geochemical research is rapidly developing new information which may greatly affect any such conclusions (Coleman and Lee, 1963; Essene and others, 1965).

Granitic Rocks and Sur Series

The Sur Series gneisses, schists, and marble, discussed by R. R. Compton in this bulletin appear to consist of thick sedimentary and perhaps volcanic formations, of possible Late Paleozoic(?) age, which have been affected by high-grade metamorphism. They crop out most extensively in the Santa Cruz and Santa Lucia Mountains where they are intruded by, and occur as inclusions in, granitic rocks. These rocks form the basement in the strip between the San Andreas and Nacimiento-Sur fault zones. No fossils have been found in the Sur Series and their structures are so complex that reasonable estimates of thickness have not been made.

Most of the granitic rocks, such as at Point Reyes, Montara Mountain, and in the La Panza high appear to be quartz diorite but granodiorite and adamellite are present. Several radiometric dates are in the Late Cretaceous range, although a number have been obtained which appear anomalous. Hornblende from a "granitic-appearing" amphibolite at Gold Hill, in the San Andreas fault zone east of Paso Robles, yielded a date of 143 m.y., or Late Jurassic (Hay, 1963). Unpublished hornblende dates I obtained from the hornblende diorite gneiss in the fault zone at Logan, San Benito County, and on hornblende from a similar rock in the fault zone about a mile south of Logan yielded dates which appear to confirm the Jurassic age of these rocks. Closer dating is not yet justified.

Most probably some of the granitic rocks are of Late Jurassic and Late Cretaceous ages and are therefore essentially contemporaneous with the Franciscan Formation. To reach their present exposed situation the granitic rocks and Sur Series must have been elevated, both by faulting and folding, by many thousands of feet—perhaps 5 miles, or more. But what is their precise relationship to the Franciscan? Since these two major rock groups are never found in anything but *fault* contact, we can only speculate on their fundamental relationship.

Upper Jurassic To Upper Cretaceous Shelf-Facies Rocks

Further to complicate relationships in the Coast Ranges and therefore also understanding of the history of the San Andreas fault, a major group of sedimentary rocks representing all epochs from Late Jurassic to Late Cretaceous age crops out in the Coast Ranges on both sides of the fault zone. They comprise an aggregate thickness on the order of 30,000 feet of unmetamorphosed shelf-facies sandstone, shale, siltstone, and minor conglomerate and limestone. They are found, in a few places, lying on the granitic rocks, Sur Series, and Franciscan, but the thickest, most continuous section lies east of the Hayward fault zone (projected) and dips under the Great Valley from the east flanks of the Diablo and Mendocino Ranges. The Late Jurassic part of this section is predominantly dark shale; the Lower and Upper Cretaceous rocks are mainly graywacke and arkose with minor shale and conglomerate. They contain larger proportions of K-feldspar grains than does the Franciscan (Bailey and others, 1964). These rocks are, at least in considerable part, contemporaneous with the Franciscan and with the granitic rocks. The older shelf-facies rocks are in fault contact with both the Franciscan and granitic rocks, but the latest Cretaceous rocks lie depositionally on each "basement" rock.

Tertiary and Quaternary Formations

Cenozoic formations comprise a great variety of sedimentary and volcanic rocks, but all are of shallow marine (shelf and slope) and continental origin. Intermittent folding, faulting, and volcanism, often of limited areal extent in this era, are reflected in rapid changes in facies and thicknesses. Most local basins of deposition were oriented in a northwesterly direction, *approximately parallel to the trend of the San Andreas fault*, and deposits were derived from a westerly or easterly direction. Facies and thickness changes are most marked at the margins of the basins and take place commonly in an east-west direction *across the trend of the San Andreas fault*. These conditions have made it particularly difficult to convincingly match rock units or facies across the fault in order to document its displacement.

Paleocene marine sedimentary rocks are quite similar to those in Upper Cretaceous formations, but are not as thick or as widespread. Progressively more restricted seaways from Paleocene to late Eocene time limited the deposition of marine sands, muds, and clays to relatively narrow basins in the area of the Coast Ranges. Paleocene and Eocene formations are found in fault blocks on both sides of the San Andreas fault in the Bay area. The presence of formations of this age only west of the fault in the coastal "Gualala" strip from Fort Ross to Point Arena suggests late Eocene or post-Eocene displacement, but whether this has been produced by strike slip, dip slip, or oblique slip is not known; the formations have not been successfully matched with those in the block east of the fault. There are, however, faulted remnants of marine Paleocene and Eocene rocks in the east block along the Middle Fork of the Eel River about 70 miles north of the Gualala strip.

From late Eocene to middle Miocene time, seaways in the Coast Range region were severely restricted and climates became markedly seasonal and locally semi-arid. Conglomerate, sandstone, shale and mudstone of these epochs include shallow marine materials and widespread, locally thick, continental red beds. Oligocene formations crop out only in the southern Coast Ranges; probably the northern Coast Range area was above sea level during Oligocene time. In the Santa Cruz, Santa Lucia, and Diablo Ranges, shallow-water marine sandstone, shale, some conglomerate, and local tuff beds represent deposits in rather restricted embayments and channels. Distribution of these sedimentary units is both east and west of the San Andreas fault in the ranges named, without any considerable lateral displacement required to explain their present position.

Early and middle Miocene formations consist of marine, shelf-facies sandstone, conglomerate, shale, and mudstone, which were deposited in rather narrow basins extensively in the southern Coast Ranges and in a narrow trough as far north as the central Mendocino Range in the northern Coast Ranges. Middle Miocene seas were more widespread than those of the early Miocene. Great volumes of volcanic materials were extruded during middle Miocene time—tuff, breccia, agglomerate, rhyolitic to andesitic flows, and plugs. Matching of such volcanic units across the San Andreas fault offers possibilities for documenting evidence of its nature and amounts of displacement, but is frustrating because of particularly rapid changes in facies and thicknesses.

In early late Miocene time shallow seas reached a maximum extent. The most widespread Tertiary formation is the Monterey Formation, of middle to late Miocene age, which is found throughout the Coast Ranges as far north as Point Arena. All common sedimentary rocks are represented, but must characteristic are siliceous shale, chert, and diatomaceous shale. The Miocene Epoch closed with deposition of coarser, sandy, marine sedimentary facies, such as the Santa Margarita, Sisquoc, and San Pablo Formations in more restricted basins between the rising Coast Ranges. The upper parts of these formations are of early Pliocene age.

In Pliocene time, sands, muds, and some tuff were deposited in narrow, shallow marine embayments throughout the Coast Ranges as far north as the Eel River basin. Most of the formations appear to thin or pinch out in the anticlinal-crest areas, reflecting uplift and folding of many of the individual ranges. Late Pliocene and early Pleistocene time was marked by restricted and thin local marine beds in narrow basins, and by a remarkably widespread and locally thick series of coarse, nonmarine sediments. Floods of gravel and coarse sand, which were deposited in the channels, deltas, and flood plains of streams, almost covered the site of the southern Coast Ranges and extended locally along the margins of the northern Coast Ranges. Volcanism was important in limited areas, but the activity did not compare with that of the great middle Miocene volcanic epoch.

In the San Francisco Bay area in late Pliocene and early Pleistocene time, a shallow, narrow seaway developed from the vicinity of Lake Merced southeastward through Merced Valley lying between the elevated blocks of the San Bruno and Montara Mountains. Over 5,000 feet of sand, silt, gravel, sandy mudstone, and layers of volcanic ash accumulated to form the Merced Formation. On the southwestern margin of this trough, and along the rift valley of the San Andreas fault, stream and alluvial-fan gravels, sand, and mud accumulated to form the Santa Clara Formation. Fossiliferous, slightly consolidated, rocks of the Merced Formation crop out in the San Andreas fault zone from Bolinas Bay for about 5 miles to the north, spreading broadly across more than 50 square miles of northern Marin County, east of the fault. Distribution and local thicknesses of the Merced and Santa Clara suggest that their deposition was strongly controlled by the San Andreas fault trough; these formations, however, spread thinly and widely both east and west of the fault.

Late Quaternary deposition is represented by coastal marine terrace deposits, bay mud, dune sands, and thin sediments along the San Andreas rift. Loosely consolidated arkosic sands crop out in the ridges and troughs within the San Andreas fault zone between Olema and Tomales Bay. Bolinas Lagoon and Tomales Bay are nearly landlocked bays in the rift valley.

STRUCTURAL HISTORY

In spite of the interests of geologists, and the very considerable amount of time and attention given by geologists and seismologists to study of the San Andreas fault, it remains very incompletely known and understood. There is no agreement on answers to such fundamental questions as: When did the fault originate? Should the Late Quaternary and "ancestral" San Andreas be regarded as different faults, developed by different stresses, and with entirely different characteristics and displacements? Have the sense and direction of displacement (right slip—east block moving south) always been the same, or has great vertical movement taken place? If the latter, which is the upthrown block? (Or has this changed from one side to the other in some segments during geologic time?) If dominantly right-lateral strike slip, has the present rate of displacement or strain, as discussed by Meade and Small in this bulletin (p. 385), been about the same since Cretaceous time? Is the cumulative displacement on the fault a few thousand feet or several hundred miles? To what depth does the faulting extend—5 or 6 miles, as suggested by the depth of earthquake foci, or several times this? Is the San Andreas fault becoming more, or less, active? Are earthquakes, which center in the San Andreas fault zone, relieving stresses and thus lessening the chances of future earthquakes, or do the continuing earthquakes merely indicate a high level of seismic activity portending many future earthquakes?

Three Great Faults

The San Andreas fault is but one of three great north-northwest-trending fault zones which appear to dominate the structural pattern of the Coast Ranges (fig. 3). The most westerly of these is the Nacimiento-Sur fault zone which separates the western coastal block of Franciscan basement rocks from the granitic block east of that fault zone. This fault is probably essentially normal, with perhaps some local right-lateral strike slip, but in its northerly projection extends into the Sur thrust zone which dips 30°–60° E. This fault zone has had a long and complex history. It comprises a large number of *en echelon* faults which are, in many places, apparently offset by cross faults. At the southern end of the Coast Ranges, the Nacimiento fault butts into the northeast-trending, left-lateral Big Pine fault yet faults farther west (for example, Suey fault) in the Nacimiento zone appear to bend continuously along the strike into the Big Pine fault At the north end of the zone, the Sur thrust enters the ocean a few miles south of Monterey. In this area, in Pfeiffer Big Sur State Park, the fault involves upper Miocene rocks but does not cut Pleistocene terrace gravels (Oakeshot, 1951). The Nacimiento-Sur fault zone does not show the rift-valley features that are so characteristic of the San Andreas, and no earthquake epicenters along its trace have been reported.

The second great fault is the San Andreas, separating the granitic block on the west from the eastern block with Franciscan "basement." As its characteristics are discussed throughout this report, they require no special treatment here.

A third great fault zone, probably related to the Nacimiento and San Andreas in origin, is the South Fork Mountain-West Valley fault, which separates a Franciscan block on the west from granitic-metamorphic rocks on the east. This fault zone constitutes the

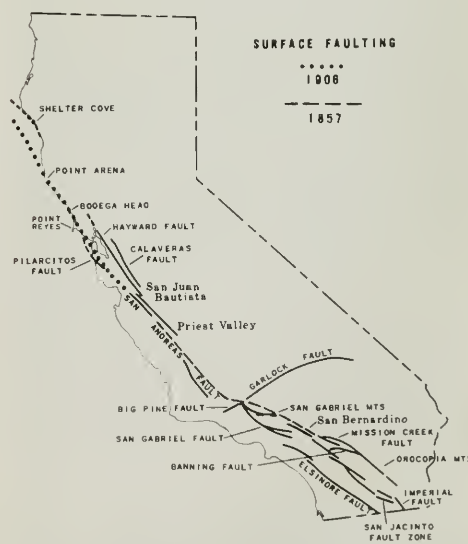

Figure 3. San Andreas fault zone, essentially as traced by Lawson and others in 1906. Dotted segment shows surface faulting in 1906; the dashed-line segment indicates surface faulting in 1857.

geologic, structural boundary between the Coast Ranges province and the Klamath-Sierra Nevada province. The South Fork Mountain fault, marked by a zone of pre-Cretaceous(?) schists several miles wide, forms the western and southwestern margin of the Klamath Mountains block (Irwin, 1960). Granitic rocks in the Klamath Mountains block, and in the western foothills of the Sierra Nevada, have yielded Late Jurassic radiometric dates. Along its southern continuation, the South Fork Mountain fault has been intruded by serpentine and appears to be overlapped by the Early Cretaceous miogeosynclinal rocks of the west side of the Great Valley. The southward projection of this great fault (Bailey and others, 1964; Oakeshott, 1964, 1965) may well form the contact between Sierra Nevada granitic rocks on the east and Franciscan rocks on the west. Gravity and magnetic anomalies mark this contact zone (Chapman, this bulletin; Griscom, this bulletin). It may have been active at the close of the Jurassic Period.

The Nacimiento-Sur, San Andreas, and South Fork Mountain-West Valley faults merge southward into the knot of major faults at the junction of the Coast Ranges, Sierra Nevada, and Transverse Ranges provinces. All three northwest-trending fault zones are completely interrupted by the east-west structures of the Transverse Ranges.

Age of the San Andreas Fault

Since there can be no disagreement that the San Andreas fault is presently active, the principal question is when movements began. Taliaferro (1943) emphasized the importance of distinguishing between the Quaternary San Andreas fault, on which displacements are still occurring, and the "ancestral" San Andreas which he regarded as "a profound normal fault developed in the early Eocene along the eastern side of the Gabilan Mesa * * *", and which always marks the boundary between the "crystalline basement complex and Mesozoic sedimentary rocks." Hill and Dibblee (1953), expressing fundamentally different views from Taliaferro, suggested very large cumulative right-lateral displacements of "perhaps 350 miles since Jurassic time," and "10 miles since the Pleistocene." Bailey, Irwin, and Jones (1964) suggest yet another mechanism in which the block west of the West Side fault separates from the eastern block in Late Jurassic time and drifts westward. The opening between blocks is filled with rocks of the Franciscan Formation and the eastern margin of the drifting block becomes the ancestral San Andreas fault. Since reaching its present position in Late Cretaceous time, Bailey suggests the fault has had no more than 50 miles of strike-slip movement.

In the segment of the San Andreas fault from the Tehachapi south, Crowell (1962) and Crowell and Walker (1962) have shown that Oligocene and all older rocks in the San Gabriel and Orocopia Mountains seem to have been displaced by the same amount. From this, and other evidence, the San Andreas fault in southern California need be no older than early Miocene. This is one of a number of profound differences between the geologic features of the fault in northern and southern California.

Evidences of mountain building in the Coast Ranges at the close of the Jurassic (Taliaferro, 1943; Page, this bulletin), accompanied by intrusion of granitic rocks and the development of narrow troughs into which great thicknesses of Franciscan sediments and volcanics were dumped, make it appear likely that development of an ancestral San Andreas fault began as early as closing Jurassic time. Repeated movements have doubtless taken place in this fault zone, accompanying other movements in orogenic epochs culminating in the greatest orogeny of the Coast Ranges in late Pliocene to mid-Pleistocene time and continuing to the present day.

Nature and Amount of Displacement

In 1953, Hill and Dibblee advanced the possibility of cumulative right-lateral displacement of hundreds of miles since Jurassic time on the San Andreas fault. This hypothesis has received very wide acceptance among earth scientists, has intrigued geologists, and has been an important factor in stimulating work on the fault. The concept of large strike slip on the San Andreas was not original with Hill and Dibblee, for Noble (1926) suggested a horizontal shift of apparently 24 miles since deposition of the "Martinez" (Paleocene) beds in the Transverse Ranges of southern California. Hill and Dibblee used lithologic, faunal, and facies similarities in attempting correlations across the fault to suggest right-lateral separation of 10 miles since the Pleistocene, 65 miles since upper Miocene, 175 miles since early Miocene, 225 miles since late Eocene, 320 miles since Cretaceous, and 350 miles since the Jurassic Period (see Dibblee this bulletin, p). This analysis is especially impressive because Dibblee had personally mapped about 300 miles along the San Andreas fault zone on the mile-to-the-inch scale. It is interesting to note that Taliaferro (1943), who had previously mapped more of the fault zone than any other geologist save Dibblee, felt less confident about such correlations and stated unequivocally that horizontal movement on the San Andreas fault north of Parkfield has been less than 1 mile!

Geologic evidence is so varied that geologists have drawn conflicting interpretations of the geologic history and characteristics of the fault; at one extreme are those who believe that there has been several hundred miles of right slip since Late Jurassic time, and at the other are those who consider that there has been large vertical displacement on an ancestral San Andreas fault and relatively small lateral displacement in Late Tertiary and Quaternary time. I have adaptd the following discussion of some of the evidence for displacement from two recent papers (Oakeshott, 1964, 1965).

Seismologic evidence, geodetic measurements, and geomorphic observations point strongly, but not entirely, to right-lateral displacement in historic and Late Quaternary-time. This type of evidence and the remarkable rift-valley features are too well known to justify more than a sketchy review here. Observers who contributed to the monumental report of the State Earthquake Investigation Commission after 1906 (Lawson and others, 1908) cited the obvious preponderance of right separation along the fault trace, up to a maximum of 20 feet; but they also noted that the western block moved relatively upward a probable maximum of 3 feet. Re-surveys of first-order triangulation nets by the Coast and Geodetic Survey suggest that strain or displacement on the San Andreas fault north of the 36th parallel has averaged about 1 to 3 cm a year since 1885, the east block moving south (Whitten, 1955; Meade and Small, this bulletin, p. 385). South of that parallel Meade and Small found no significant horizontal displacement but do cite evidence of uplift (this bulletin). In a talk presented to the Stanford Journal Club in October 1963, Robert D. Burford reported on an analysis of C. A. Whitten's vectors across the San Andreas fault system near Hollister. His analysis showed right displacement on the northwest-trending faults, left displacement on two northeast-trending faults, and extension at right angles to the trace of the San Andreas fault. He concluded that displacement near the San Andreas fault in that locality has been at the rate of 3 cm per year, and a few miles to the west and east, at the rate of 2 cm per year. Wallace (1949) computed a displacement of 0.2 inch per year since 1857 by adding known displacements associated with historic earthquakes.

Tocher (1960) has measured slow creep at the winery south of Hollister at about half an inch per year. This occurs in "spasms" of a few days, separated by intervals of weeks or months. Hill and Dibblee (1953) computed average displacement of 0.2 to 0.3 inches per year, based on their postulated movements for various ages as far back as Late Jurassic time. Cluff (1965) and Radbruch (1965) have reported several cases of well-substantiated right-lateral creep on the order of an eighth to a quarter of an inch per year, averaged for about 40 years, along the 1868 trace of the Hayward fault from Irvington to the University of California Stadium.[1]

Recently, the State Department of Water Resources, in its crustal strain investigation program (Gibson, 1961, and State Department of Water Resources, 1963), has made geodimeter measurements of 2,600 miles of surveying across the San Andreas and related faults. That Department's statement is "* * * a preliminary evaluation of measurements across the San Andreas fault suggests right-lateral movement between Hollister and Simmler. The few repeat measurements available between Simmler and the intersection of the San Andreas and Garlock faults [farther south] suggest left-lateral movement. South of the Garlock fault, it has not been possible to establish a consistent pattern of movement."

An interesting departure from the pattern of right-slip movements has been recorded by Tocher (1959) for the San Francisco earthquake of March 1957. In applying Byerly's method for deducing the nature of faulting from seismograms, Tocher concluded that the movement causing that earthquake was not a repetition of the observed right-lateral movement of 1906, but instead was largely vertical displacement on a steeply dipping reverse fault with the east block moving relatively upward. Thus, it would appear that increments of movement on the San Andreas fault may be of different sense at different times and places.

Most of the geomorphic evidence for Quaternary displacement on the San Andreas fault has been based on offset drainage features. Nature of the evidence may be seen from the following examples: Noble (1926) reported four deep ravines which were offset 150 feet at a point 3 miles southeast of Cajon Pass; Allen (1946) noted offsets of drainage amounting to 3,800 feet in the Gabilan Range; Wallace recorded drainage features offset up to 1½ miles on the north side of the San Gabriel Mountains; and Hill and Dibblee saw 3,000 feet of stream offset in the Temblor Range. Higgins (1961) did detailed mapping in the fault zone north of San Francisco Bay and concluded that there the fault was active before middle Pliocene time, but that the evidence was insufficient to allow determination of either the type or amount of pre-middle Pliocene displacement. None of the anomalous stream courses in that area gave clear evidence of lateral displacement; all can best be attributed to deflection by slides or earthflows, to headward erosion along softened rocks in the fault zone, to vertical movement of fault slivers, and to other minor structural controls within the fault zone. Galloway (1962) has been working on these problems in the San Andreas fault zone in the Bolinas-Point Reyes area for several years. His detailed mapping in the zone has disclosed no evidence of either the sense or amount of displacement.

Seismologic evidence, geodetic measurements, and geomorphic observations generally strongly suggest right slip in very late Quaternary time, but also indicate that the sense of movement in increments of slip has not always been the same. *Extrapolation of this very short experience back over geologic periods of many millions of years appears wholly unjustifiable.*

Unraveling of the pre-Quaternary history of the San Andreas fault is much more difficult than deciphering its later history, and uncertainties multiply as we attempt to trace the fault displacements back into Early Tertiary time and to document a possible pre-

[1] See six related papers on Slippage on the Hayward fault: (Cluff and Steinbrugge, 1966; Bonilla, 1966; Blanchard and Laverty, 1966; Radbruch and Lennert, 1966; Bolt and Marion, 1966; Pope, Stearn, and Whitten, 1966).

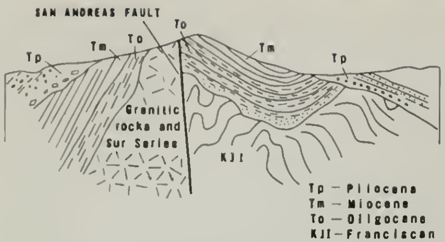

Figure 4. Diagrammatic section near Pajaro Gap, Santa Cruz-San Benito Counties, showing similarity of geologic units on both sides of San Andreas fault.

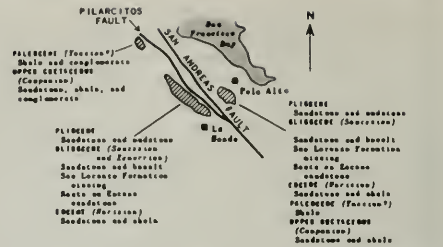

Figure 6. Big Basin area, Santa Cruz Mountains, showing how Cretaceous and Tertiary rocks correlate across the San Andreas fault zone. After Cummings, Touring, and Brabb, 1962.

Tertiary history. We shall now examine a small part of that evidence in selected areas in the segment north of the Tehachapi (more completely reviewed in Oakeshott, 1965).

Figure 3 shows the San Andreas fault much as it was mapped by Lawson and others, in 1906, and it also includes other faults that will be discussed. The dotted segment of the fault, from San Juan Bautista to the ocean north of Point Arena, denotes the surface fracture associated with the 1906 San Francisco earthquake. Surface faulting (east block raised) that took place at the same time along an *en echelon* fault at Shelter Cove in southern Humboldt County is indicated by the northernmost fault line. On the San Francisco peninsula the Late Quaternary San Andreas fault

Figure 5. Pattern of faults in the Pajaro River area, according to Allen (1946).

departs from the old major fault zone as the important fault which separates distinctive geologic units here is the Pilarcitos, not the San Andreas as named by Lawson (1908). Surface faulting which took place at the time of the 1857 Fort Tejon earthquake, from Priest Valley to San Bernardino, is shown by the dashed-line segment in that area.

Figure 4 is a diagrammatic section (my field interpretation from Allen, 1946) representing the rock formations that are exposed in the Pajaro River Gap and vicinity across the southern end of the Santa Cruz Mountains. Figure 5 shows the pattern of faulting in this area, according to Allen (1946). Here the San Andreas fault is unusually well exposed. Basement rocks in the west block consist of the Sur Series gneisses and schists of pre-Cretaceous age which have been intruded by Late Jurassic and Cretaceous granitic rocks. On the east are the complex rocks of the Late Jurassic to Late Cretaceous Franciscan Formation. Three Tertiary formations, which are exposed above the basement rocks on both sides of the fault, appear lithologically, structurally, and stratigraphically identical. Oligocene marine shale crops out on both sides of the fault and grades upward into the distinctive, thin-bedded sandstone and siliceous shale of the Miocene Monterey Formation. Unconformably lying on the Monterey Formation on both sides of the fault are the much coarser sandstones and conglomerates of the Pliocene Purisima Formation. The Purisima overlaps the older Tertiary units to lie unconformably on Franciscan in the east block and on granitic rocks and Sur Series on the west. At one nearby locality the basal beds of the Purisima that lie on granitic rock contain an abundance of extremely coarse clasts of Franciscan rocks which must have come across the fault zone. There is thus no evidence for, and no necessity for, large Tertiary or post-Tertiary displacement on the San Andreas fault in this region.

In figure 4 the west side of the section is the southern end of the Santa Cruz basin, the east side is the north end of the Hollister Trough. If there has been large-lateral displacement on the San Andreas fault, these two Tertiary basins would not be continuous but would be matched by sedimentary-rock sections many miles apart across the fault. After years of work in this region, Gribi (1963) recently had this to say:

> "'Slippers' would match the Hollister Trough sediments with rocks in same basin far to the northwest on the west side of the San Andreas fault. However, the rocks from Eocene into middle Miocene of the southeast end of the Santa Cruz Basin are similar to their counterparts immediately across the fault in the northwest end of the Hollister Trough in lithology, thickness, and faunal content. Upper Miocene and Pliocene rocks show some differing characteristics, but these differences are no greater than have been demonstrated by simple facies and thickness changes in similar rocks in areas not affected by lateral faulting. Therefore, as a working hypothesis here it is assumed that the Hollister Trough is the depositional and structural continuation of the Half Moon Bay-Santa Cruz Basin. With its definite connection to the San Benito Trough, Vallecitas Syncline, Priest Valley-Warthan Canyon Syncline, the San Joaquin Valley, and probably the Bitterwater Basin and the Salinas Basin, the Hollister Trough becomes an integral part of California Tertiary sedimentary history and particularly of a great linear zone of weakness, a portion of which coincides with the present-day San Andreas fault."

At San Juan Bautista, about 6 miles southeast of Pajaro Gap, the west block of the fault, in which Sur Series gneisses and granitic rocks are exposed, is at least 10,000 feet structurally higher than the Hollister Trough immediately across the fault to the east.

Farther north in the Santa Cruz Mountains, Brabb (1960) and associates (Cummings, Touring, and Brabb, 1962) did large-scale, detailed geologic mapping west of the San Andreas fault and compared the Late Cretaceous-to-Pliocene geologic columns and histories across the San Andreas-Pilarcitos fault zone, as shown on figure 6. Lithology, stratigraphy, fossil zones, and geologic history correlate so strikingly across the faults here from Late Cretaceous (Campanian) to Pliocene time as to apparently preclude any cumulative offset measurable in miles since the Late Cretaceous. Evidence from the given examples of matching geology across the fault suggests that there are no compelling geological reasons for lateral displacements measurable in miles since Late Cretaceous (Santonian?) time.

It is evident that, in the present state of knowledge, the origin, nature, and history of movement on the San Andreas and related faults are not clear. Late Quaternary evidence strongly, but not exclusively, favors predominant right-slip displacement. Late Cretaceous and Tertiary stratigraphy, structure, and geologic history which can be matched across the fault in central and northern California leave little room for strike-slip displacement of more than a mile or two. Abrupt thickness and facies changes in rock units of these ages and very complex structures throw great difficulties in the way of matching geological elements across the fault. Distribution of Late Mesozoic Franciscan rocks and granitic rocks of near-equivalent age cannot be satisfactorily explained by large strike-slip movement, but does appear to require vertical displacements on the order of more than 10 miles. *For the present, geologists, seismologists, and geophysicists should retain multiple working hypotheses concerning displacement on the San Andreas and related major faults.*

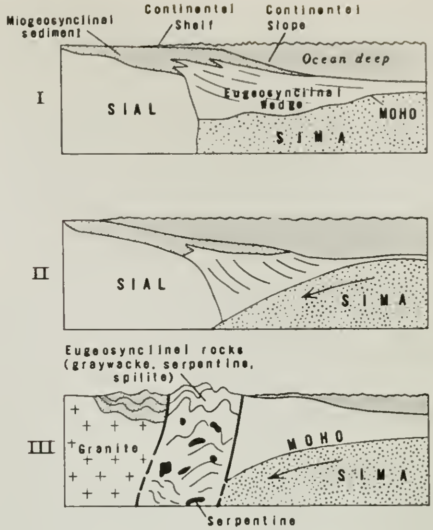

Figure 7. Stages in Alpine orogeny, after Dietz, 1963, with hypothetical faults added.

ORIGIN OF THE FAULT SYSTEM

How and why did the San Andreas fault system, including its associated northwest-trending fault—the Nacimiento-Sur and the South Fork Mountain-West Valley faults—originate?

Here we move into the realm of speculation, but we are not wholly without some basis for discussion. We have noted earlier that geologic relationships between the Franciscan Formation and the granitic blocks seem to require absolute vertical elevation of the Franciscan on the order of 10 miles, and elevation relative to the granitic segments of the crust of an unestimated amount. Bailey (1963) and Bailey and others (1964) proposed westward continental drifting and rifting to form "sphenochasms" between blocks of continental crust, thus providing sites for deposition of the Franciscan Formation directly on sima. In any case, initiation of this great faulting at the juncture of the ocean basin and continental platform was probably in closing Jurassic time; additional first-order faulting took place in Late Cretaceous time. Slivers and pods of ultramafic rocks were caught up and intruded into the lower part of the Franciscan from the upper mantle at the time the eugeosynclinal trough reached its maximum depression. Figure 7, after Dietz (1963A, 1963B), suggests how this sort of thing might happen. This diagram shows three stages in alpine orogeny after Dietz' concept of geosynclines and mountain building, a concept which appears compatible with the great fault features of western California which have been so briefly outlined. I have modified his diagrams somewhat and have added hypothetical faults in stage III.

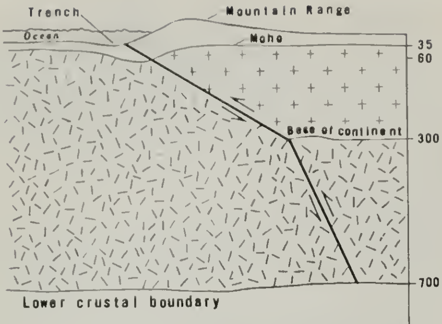

Figure 8. Continental crustal section with orogenic fault type. *After Benioff, 1954.*

The three stages as applied to the Coast Ranges might be:

I. Franciscan sediments and volcanics are rapidly deposited in a eugeosynclinal wedge at the base of the continental slope, generally seaward from nearly contemporaneous deposition of shelf, or miogeosynclinal, deposits.

II. Sea-floor spreading (under a force perhaps supplied by thermal convection cells in the mantle) provides the initial thrust which causes the sima to slip under the sial of the continent. The bottom of the prism of deep-sea turbidites is forced even deeper and is intruded by, and picks up, fragments of the simatic basement.

III. The mantle tends to shear beneath the continental platform, granitic intrusion begins early in the thrusting, and the prism is intensely folded, faulted, and elevated to form coastal mountains. The generalized, diagrammatic faults emphasize the prominent role that steep, dip-slip, reverse faults probably play in this history.

Benioff (1954) studied the elastic strain-rebound characteristics and related spatial distribution of foci of hundreds of seismic sequences to demonstrate the characteristics of oceanic and marginal orogenic faults. Figure 8 is his diagram showing a continental crustal section with orogenic fault type. The fault-dip angles of 32° to a depth of 300 km and 60° to 700 km should not be taken quantitatively, but it is significant that seismology, quite independently, develops a diagram showing deep major faulting extending under the continental margin and dipping toward the continent. Although the San Andreas fault appears to be nearly vertical, it is quite possible that it flattens near the Moho and that Benioff's section is more applicable than it appears to be at first glance.

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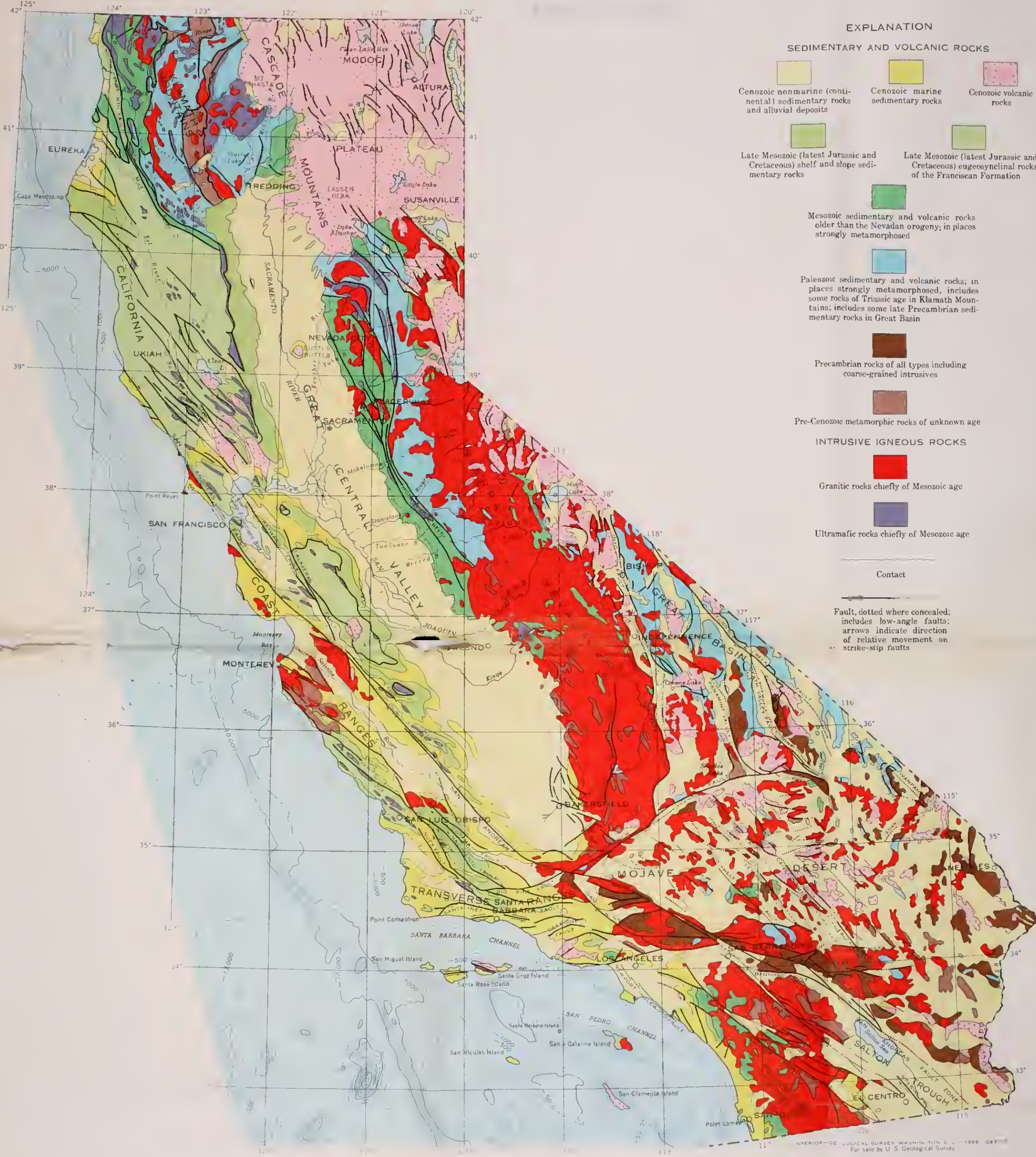
DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

- Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits
- Cenozoic marine sedimentary rocks
- Cenozoic volcanic rocks
- Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks
- Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation
- Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed
- Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin
- Precambrian rocks of all types including coarse-grained intrusives
- Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

- Granitic rocks chiefly of Mesozoic age
- Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1966
For sale by U. S. Geological Survey

GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1:2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET. DATUM IS SEA LEVEL

1966