EVIDENCE FOR CUMULATIVE OFFSET ON THE SAN ANDREAS FAULT IN CENTRAL AND NORTHERN CALIFORNIA *

By T. W. Dibblee, Jr.
U.S. Geological Survey, Menlo Park, California

INTRODUCTION

It is agreed among all geologists who have investigated the San Andreas fault that the latest movements are horizontal in the right-lateral (dextral) sense. However, as indicated in the preceding summary article, geologists do not agree on the type, direction, and magnitude of earlier movements. Their interpretations vary according to the parts of the fault they have investigated, and with the way in which they have mapped and interpreted the related geology.

The geology on both sides of all but a few segments of the San Andreas fault has been mapped or partly mapped by the writer, and his initial interpretations of the time, direction, and magnitude of movements on this master fault have already been presented (Hill and Dibblee, 1953, p. 445–450). Additional field observations by the writer since that time cast more light on those inferences, calling for some modifications in magnitude, but do not alter the basic concept of large cumulative right-lateral movement since the inception of this generally vertical fault.

This progress report presents the evidences of lateral offsets, as now interpreted, on the central and northwestern parts of the San Andreas fault—the parts within the Coast Ranges province. The latest offsets are most clearly discernible and are described first, followed by descriptions of earlier offsets which become progressively less discernible with age. For evidence of right-lateral offsets on the southern continuation of the San Andreas fault southeast from Gorman, the reader is referred to descriptions by Noble (1954) and Crowell (1960, 1962).

* Publication authorized by the Director, U.S. Geological Survey.

Photo 1. Aerial view southwest across low scarp of San Andreas fault exposed in the Carrizo Plain, Painted Rock quadrangle. Arroyo in Quaternary alluvial sediments shows 400 feet of right-lateral offset along fault.

OFFSETS DURING QUATERNARY TIME

Physiographic features formed by the latest Quaternary lateral movements on the San Andreas fault are described in detail in many publications that describe the fault. Most stream channels that drain southwestward across the fault are consistently offset to the northwest, and those that drain northeastward across it are offset to the southeast. These relations can be seen along the entire 600-mile known length of the fault and are the most positive evidence of right-lateral movement. Offset stream channels are especially evident in the Carrizo Plain where some channels that drain southwestward from the Temblor Range apparently are offset as much as 3,000 feet (Hill and Dibblee, 1953, p. 446). In the Santa Cruz Mountains a number of channels, including the Pajaro River, are offset about 3,800 feet (Allen, 1946, p. 50). North of San Francisco similar offsets near Point Arena have been described by Higgins (1961, p. 53, 59). These displacements occurred in very late Pleistocene and Recent times, perhaps during the last 30,000 or 40,000 years. This would amount to about 1 inch of right-lateral movement per year during that interval.

Photo 2. View southwest across San Andreas fault in Carrizo Plain, McKittrick Summit quadrangle, showing at least two, and probably three, offsets. Recent(?) right-lateral movement of nearly 100 feet is shown by abrupt bend in pair of channels in crossing the fault. Larger, and older, offset is indicated by the headless pair of channels on right, and an intermediate offset probably is indicated by less well-developed swales to left of road beyond fault.

Displacements since earlier Quaternary time can be inferred by comparing the detrital fragments of Pleistocene alluvial gravel adjacent to or near the fault, particularly the early or middle Pleistocene gravel, and by relating these gravels to their probable source rocks. This is especially significant because throughout Quaternary time segments on both sides of the fault were elevated and shed detritus, the gravel accumulating in valleys or lowlands on the opposite side. Thus it is possible to determine the source area of much of the Pleistocene gravel adjacent to the fault, especially if some unique or particularly distinctive rocks are involved; and if the source area has been shifted from its original position by lateral movement on the fault one may estimate the amount of shift since the gravel accumulated. Similar inferences can be applied to Pleistocene landslide masses that may have slumped across the fault.

In the north-central Santa Cruz Mountains (fig. 1), about 2,000 feet of Pliocene and Pleistocene alluvial gravels, the Santa Clara Formation, occurs on both sides of the San Andreas fault. East of the fault the gravel is composed of detritus of the Franciscan Formation derived from the adjacent mountains lying on the same side of the fault. Remnants of the gravel on the west side contain Franciscan detritus. But in addition the gravel contains abundant boulders of a distinctive cobble conglomerate and fragments of sandstone and shale lithologically identical to Upper Cretaceous(?) conglomerate, shale, and sandstone now exposed only on the east side of the fault some 20 miles southeast on Loma Prieta Mountain (fig. 1). If that area was the source of the fragments, the gravels provide evidence of the amount of movement along the fault since their deposition.

Farther southeast, on the west side of the San Andreas fault near Peachtree Valley northeast of Salinas Valley (fig. 2), about 1,000 feet of Pliocene and Pleistocene(?) alluvial gravel, the Paso Robles Formation, unconformably overlies lower Pliocene siliceous mudstone which rests on granitic basement. The gravel, however, is composed mostly of Franciscan detritus and dips under a strip of shattered Franciscan rocks and serpentine adjacent to the fault. Either these shat-

Photo 3. View northwest along San Andreas rift zone in Santa Cruz Mountains in northern part of area shown on figure 4. Long straight canyon draining to lower right is that of Stevens Creek, which follows the San Andreas fault. Mountains left of fault underlain by marine sedimentary rocks of lower Miocene age; mountains to right of fault, including grass-covered Black Mountain, are underlain by Franciscan eugeosynclinal rocks which here are Cretaceous in age.

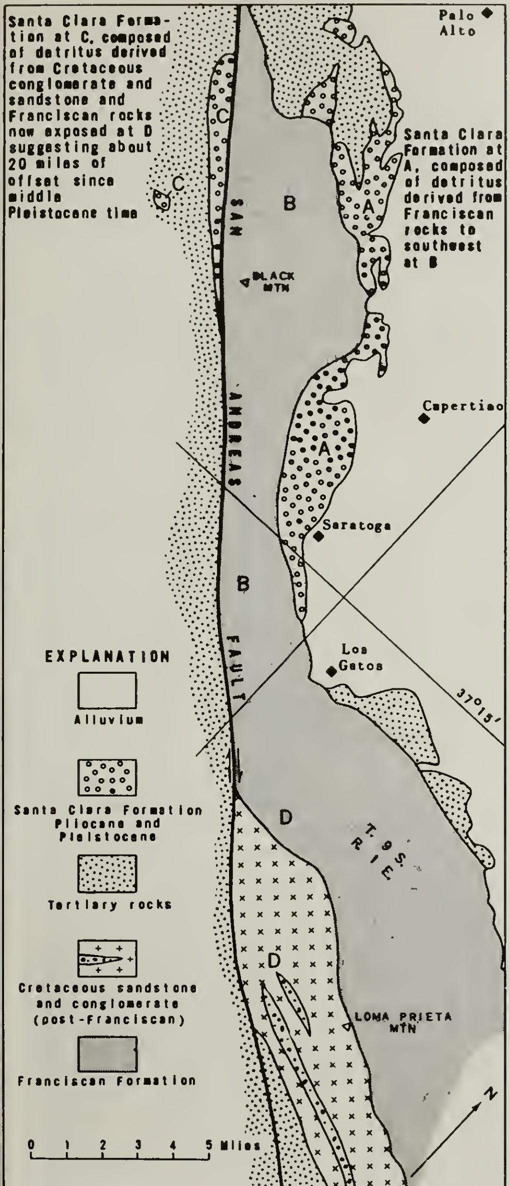

Figure 1. Evidence of late Quaternary right-lateral offset on San Andreas fault in the Santa Cruz Mountains.

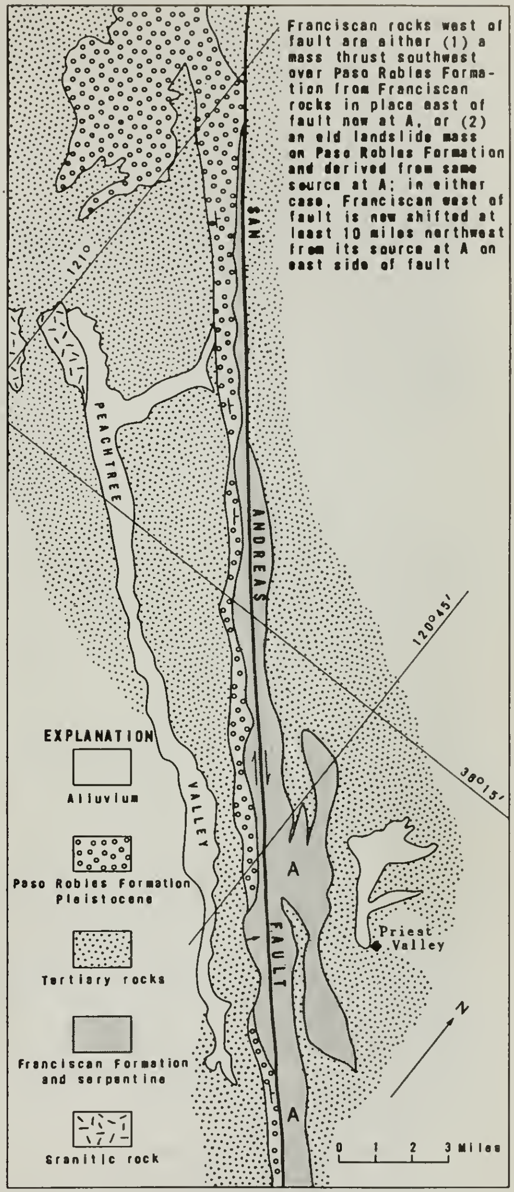

Figure 2. Evidence of late Quaternary right-lateral offset on San Andreas fault in Peachtree Valley area.

tered rocks were thrust over the gravel or they slumped over it from the northeast. In either case the source rocks must have been in the large mass of Franciscan rocks and serpentine northeast across the fault, but which now are some 10 miles to the southeast (fig. 2).

A few miles northwest of Peachtree Valley, in Bear Valley east of the Gabilan Mountains, additional suggestion of offset may be obtained from somewhat complex relations. Here lower Pleistocene gravel, the San Benito Gravels of Lawson (1893), lies on marine Pliocene sediments on the east side of the San Andreas fault; but on the west side of the fault this same gravel is underlain by brecciated Franciscan rocks. These rocks west of the San Andreas fault were mapped as being in *fault contact* on their west with Miocene sediments lying on granitic basement of the Gabilan Mountains (Wilson, 1943, pl. III). Interpretations on these relations vary greatly (Wilson, 1943, p. 227, 251–253; Hill and Dibblee, 1953, p. 449), and it is not certain whether this contact between the Franciscan and the Miocene rocks is a major fault, a minor fault, or an unconformity. It appears most likely that there is an unconformity at the base of the gravel, and that the Franciscan rocks beneath are landslide, or possibly overthrust, masses. If so, these Franciscan masses can have had no local source and probably were derived from the area of Franciscan rocks exposed at A in figure 2 before the gravel was deposited. If this is a correct interpretation, it suggests a right-lateral offset of at least 20 miles since the basal part of the San Benito Gravels was deposited.

Still farther southeast, the valley of Carrizo Plain is partly filled with lower Pleistocene alluvial gravel, in this area assigned to the Paso Robles Formation, to a depth of about 2,000 feet. In the southeast end of this plain and southeastward (fig. 3), much of the gravel on the east side of the San Andreas fault is composed of siliceous shale pebbles derived from Miocene siliceous shale of the adjacent Temblor Range. But on the west side of the fault, gravel of the same age is composed of detritus and small landslide masses derived from distinctive crystalline rocks and Tertiary sedimentary rocks now exposed a dozen miles to the southeast in the San Emigdio Mountains east of the fault (fig. 3). These relations strongly suggest that right-lateral shift on the fault since deposition of the early Pleistocene gravel has been about 12 miles.

Similar offsets of Pleistocene gravel on the fault have been found still farther southeast in the Mojave Desert region near Palmdale.

DISPLACEMENTS OF PLIOCENE FORMATIONS

In the Santa Cruz Mountains, as shown on figure 4, the northern limit of fossiliferous marine sandstone and siltstone of the Purisima Formation of early and middle Pliocene age east of the San Andreas fault appears to be offset some 20 miles, or possibly 40 miles, from its northern limit west of the fault. This offset suggests a lateral displacement of this magnitude since deposition of the Pliocene marine sediments.

Similarly, in the Salinas Valley-Carrizo Plain region far to the southeast, shown on figure 5, the southern limit of lower to middle Pliocene marine formations exposed east of the fault near Carrizo Plain appears to be offset about 50 miles from the southern limit of its counterpart west of the fault in Salinas Valley. Well data in the Salinas Valley indicate that these marine sediments extend southward under the alluvium not more than 12 miles, south of which the Pliocene is entirely nonmarine.

DISPLACEMENTS OF MIOCENE FORMATIONS

West of Bakersfield on the east flank of the Temblor Range, east of the San Andreas fault, the uppermost Miocene section is a marine diatomaceous shale, commonly called the Reef Ridge Shale. But to the southwest within this range the shale intertongues into a coarse breccia facies of granitic rock, schist, and marble detritus which consists in part of several landslide masses of these rocks. Obviously this coarse detritus was derived from an adjacent mountain range of crystalline rocks that must have been prominent in the area directly west across the fault in late Miocene time. This source has since been shifted many miles away, presumably to the northwest, because upper Miocene sedimentary rocks underlie much of Carrizo Plain to the west, as indicated by drill holes. The nearest possible source of such crystalline rocks without a cover of upper Miocene sediments west of the fault is now in the Gabilan Range some 80 miles to the northwest, suggesting a right-lateral displacement of that amount since late Miocene time (Dibblee, 1962, p. 8).

In the Carrizo Plain, Caliente Range, and southeastward, west of the San Andreas fault, as shown on figure 6, much of the upper and middle Miocene section is marine and locally contains abundant large tropical shallow-water molluscan fossils. Eastward in these areas the section grades laterally into nonmarine red beds. Toward the fault these red beds coarsen into conglomerate composed of detritus derived from an area of granitic and metamorphic rocks that presumably existed east of the fault. However, in the Temblor Range and western San Emigdio Mountains, on the east side of the fault, the equivalent Miocene section is *all marine*, composed of shale with deep-water microfaunas, and standstone with sparse, dwarfed molluscan faunas. In going eastward this marine section grades laterally through littoral sands into nonmarine sediments at the eastern margin of southern San Joaquin Valley, giving relations like those in the area west of the fault. The transition zone from marine to nonmarine beds, or strand line, if once continuous across the fault, has been displaced since Miocene time by cumulative right-lateral movement on the fault, as shown on figure 6 (Hill and Dibblee, 1953, p. 446–448;

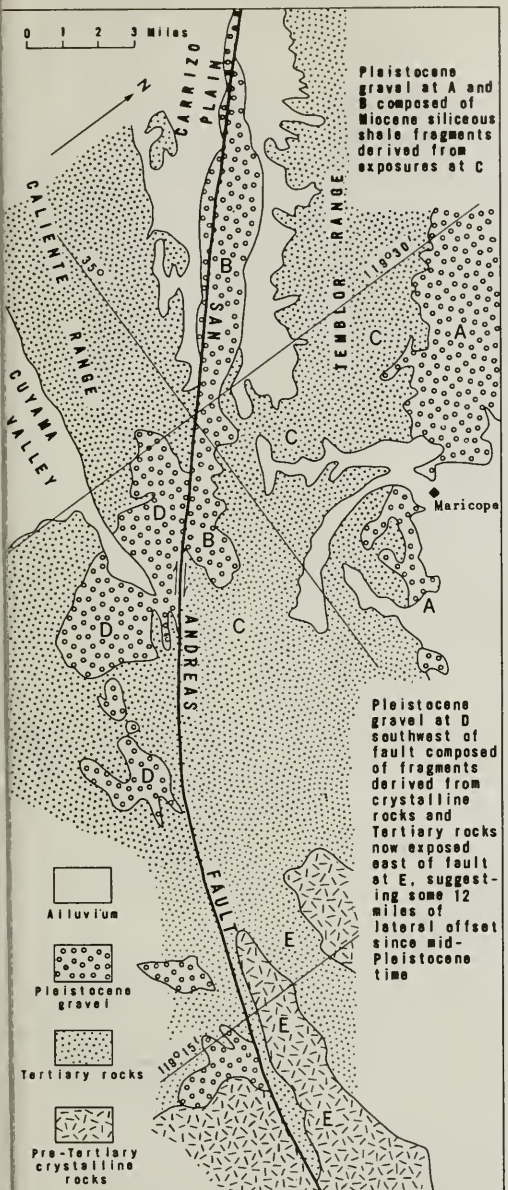

Figure 3. Evidence of late Quaternary right-lateral offset on San Andreas fault southeast of Carrizo Plain.

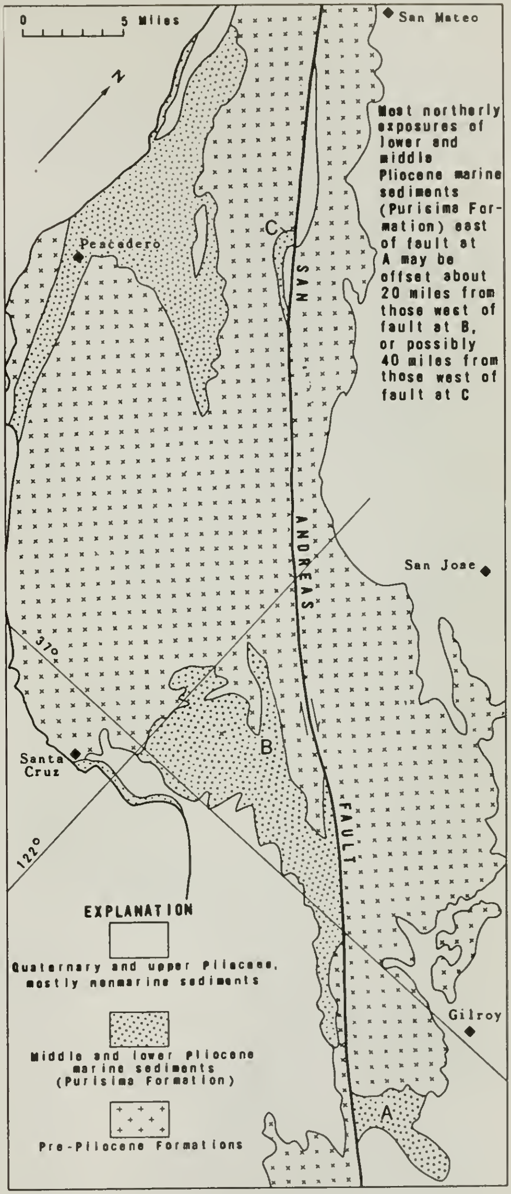

Figure 4. Evidence of right-lateral offset on San Andreas fault since middle Pliocene time in the Santa Cruz Mountains.

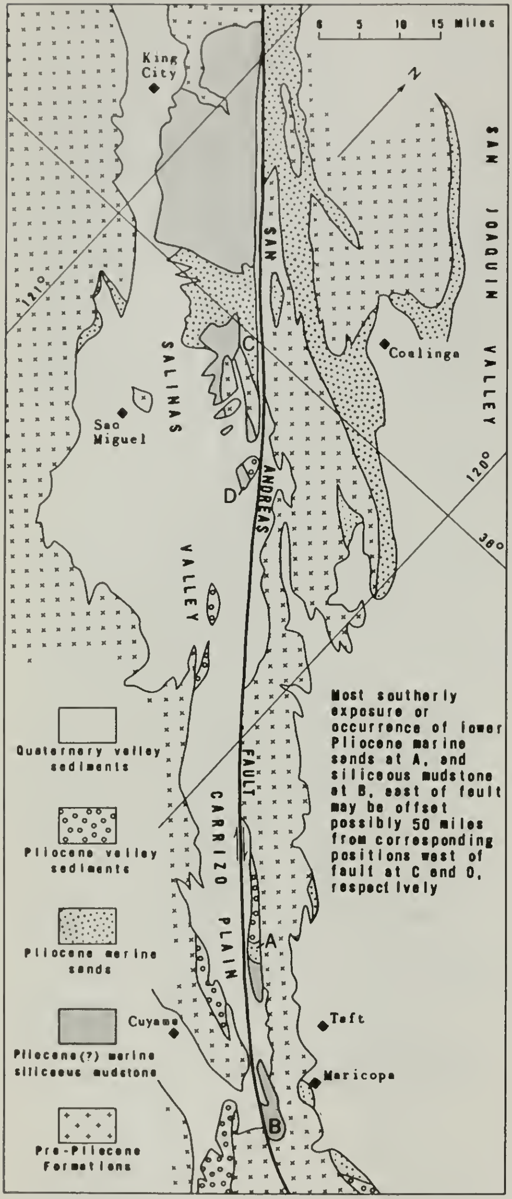

Figure 5. Evidence of right-lateral offset on San Andreas fault since early Pliocene time in the area from King City to Cuyama.

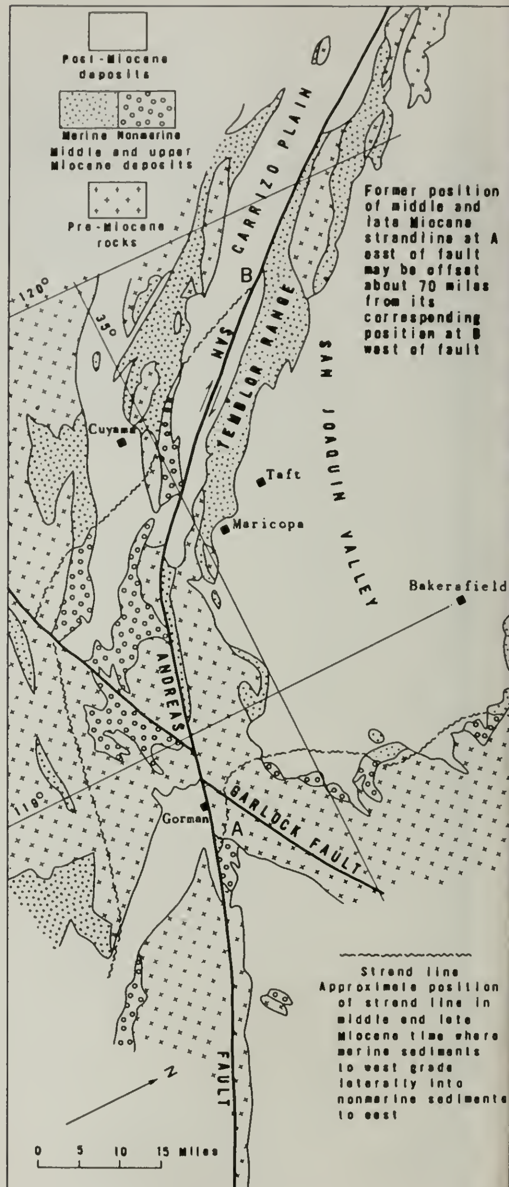

Figure 6. Evidence of right-lateral offset on San Andreas fault since late Miocene time in the vicinity of southern San Joaquin Valley.

Dibblee, 1962, p. 5). Because of possible irregularities in the strand line the post-Miocene offset cannot be precisely determined, but it is apparently about 70 miles.

DISPLACEMENTS OF OLIGOCENE AND LOWER MIOCENE FORMATIONS

West of the San Andreas fault, sedimentary rocks of Oligocene and lower Miocene (Refugian and Zemorrian) age are present in many areas. In the Santa Cruz Mountains they are all marine and are assigned to the San Lorenzo Formation and Vaqueros Sandstone. To the southeast, at the north end of the Gabilan Range (about 15 miles east of Monterey Bay), the sandstone becomes nonmarine and includes volcanic flows. Southeastward from the Gabilan and Santa Lucia Mountains the lower part of the section is all nonmarine throughout the State except in the Point Conception area.

East of the San Andreas fault, Oligocene and lower Miocene formations are recognized in southern San Joaquin Valley and the bordering hills and mountains. The formations here are all marine northwestward from the San Emigdio Mountains. In these mountains, the lower part of the section is represented by the marine San Emigdio Formation, which is lithologically and faunally similar to the San Lorenzo Formation west of the San Andreas fault, and the overlying marine sandstone grades eastward into nonmarine beds which contain volcanic flows, similar to the nonmarine beds at the north end of the Gabilan Range west of the fault. Farther east, around the southeast end of San Joaquin Valley, the entire section becomes nonmarine. If the strand line between marine and nonmarine beds was once continuous across the fault, it has been displaced about 175 miles since early Miocene time (Hill and Dibblee, 1953, p. 448–449).

DISPLACEMENTS OF EOCENE FORMATIONS

Formations of Eocene, Paleocene, and Late Cretaceous age throughout the Coast Range and Great Valley provinces are nearly all marine and clastic sedimentary rocks, with no strand-line offset by the San Andreas fault. Lateral displacements of the marine sections could be great but would be very difficult to recognize. The lithologic and faunal similarities of the Eocene section of the San Emigdio-Temblor Range to that of the Santa Cruz Mountains suggests some 225 miles of separation since late Eocene time, as noted by Hill and Dibblee (1953, p. 449).

DISPLACEMENTS OF MESOZOIC FORMATIONS

The San Andreas fault forms the boundary between an area of granitic-metamorphic basement on the west and an area of Franciscan and serpentine basement to the east. Nowhere are these two vastly different basement types found in depositional or intrusive contact, although laboratory and fossil studies seem to suggest that they are both within the same age range in the Mesozoic (Bailey, Irwin, and Jones, 1964, p. 154, pl. 1). If this is so, then their juxtaposition must be the result of large lateral movement on the fault. The 350-mile right-lateral displacement of the contact between these basements from near the southern end of the San Joaquin Valley to some point undersea northwest of Point Arena, as postulated by Hill and Dibblee (1953, p. 449), is therefore still a possibility.

OTHER DISPLACEMENTS ON NORTHERN PART OF SAN ANDREAS FAULT

On the segment of the San Andreas fault zone northwest of San Francisco the pre-Pleistocene rock units on opposite sides are entirely dissimilar. Near the fault zone none of the rock units present on one side are present on the other. This segment separates a western area of granitic basement overlain by marine sandstone and shale of latest Cretaceous, Eocene, and early Miocene age, marine siliceous shale (Monterey) of Miocene age, and marine diatomaceous mudstone (Purisima) of early Pliocene age, from an eastern area of Franciscan rocks overlain by nonmarine and volcanic rocks of Pliocene age and marine sands of middle(?) and late Pliocene age. This juxtaposition of dissimilar sequences along the fault zone must be the result of very large cumulative lateral displacement. The fault is also strongly expressed physiographically by a rift zone that offsets streams in a right-lateral sense. There is no indication of any decreasing displacement as it enters the ocean near Point Arena.

Higgins (1961, p. 67) infers that there was probably not more than 1 or 1½ miles of right-lateral displacement on the fault since deposition of the marine Pliocene sands first began east of the fault. However, owing to the absence of the Pliocene sands west of the fault there seems to be no positive way to determine the displacement on this part of the fault since that time.

The Pilarcitos fault in the northern Santa Cruz Mountains is an important branch of the San Andreas fault. While it shows little topographic expression, and no physiographic evidence of Recent or late Pleistocene activity, it, rather than the San Andreas fault, forms the boundary between the area of Franciscan basement and the area of granitic basement to the west, as shown on figure 7. It presumably rejoins the San Andreas undersea west of the Golden Gate. The Pilarcitos fault in most places dips steeply northeastward toward the San Andreas fault. Throughout the narrow strip between these two faults, the sequence and structural relations of rock units from Franciscan to and including the Miocene Monterey Shale is much the same as that of the block northeast of the San Andreas. The sequence is, however, shifted northwesterly from its counterpart northeast of the fault about 20 miles, as shown on figure 7.

Photo 5. View southeast along San Andreas fault from over south end of Tomales Bay. Dark peak in upper left is Mount Tamalpais. In this area the San Andreas rift zone is marked by two parallel branches, half a mile or less apart, bounding the alluviated valley. Timbered mountains on the right have a granitic basement overlain by Miocene sandstone and siliceous shale; hills and mountains left of fault are composed chiefly of Franciscan rocks.

Photo 4. Aerial view northwest along San Andreas fault in the Elkhorn Hills in Carrizo Plain, Elkhorn Hills quadrangle. Uplifted and dissected area traversed by the fault is composed of the Pleistocene alluvial sediments of the Paso Robles Formation. The black streak at the left edge of the hills is not the result of faulting, but is formed by tumbleweed collecting along a fence line. Temblor Range at upper right is underlain by Miocene sedimentary rocks.

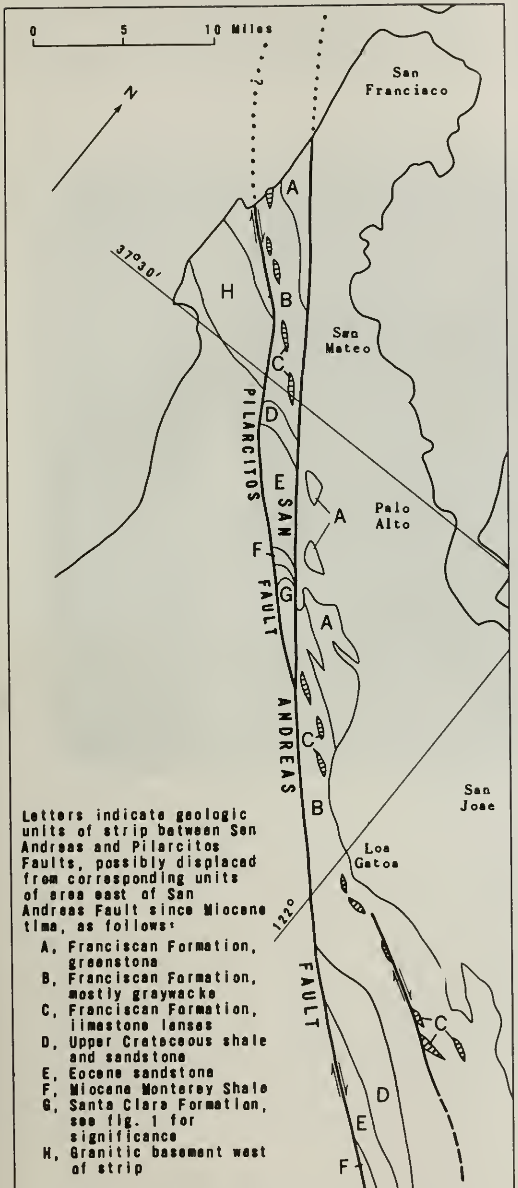

Figure 7. Evidence of right-lateral offset of strip between Pilarcitos and San Andreas faults in northern Santa Cruz Mountains.

The above relation strongly suggests that the Pilarcitos fault was the main active line of movement of the San Andreas zone until after deposition of the Miocene Monterey Shale. The marine Pliocene sandstone that unconformably overlies the Monterey Shale in the area between the faults is similar to that west of the Pilarcitos fault and probably accumulated across it, as did the Santa Clara Gravel. This suggests that since Pliocene time the Pilarcitos fault has been inactive and the present San Andreas fault has been the active line of movement.

In the New Almaden mining district southeast of Los Gatos, the Franciscan rocks, which here dip mostly to the northeast, are transected by a pre-Tertiary shear zone (Ben Trovato shear zone) and associated minor north-branching faults, about 5 miles east of and parallel to the San Andreas fault. The stratigraphic portion of the Franciscan rocks that contains discontinuous lenses of limestone is apparently offset several (less than 10) miles in a right-lateral sense on this shear zone (see fig. 7), as postulated by Bailey and Everhart (1964, p. 79, 80, 91, pl. 1).

CONCLUSION

From both the physiographic expression and the geologic relations it seems evident that the San Andreas fault is a generally vertical plane of right-lateral shear movement active during most, if not all, of the Cenozoic Era, with very large cumulative offset or displacement. This is indicated or suggested not only by the displacements of geologic units that have been described, but also by the structural pattern associated with the fault. This pattern is expressed in the severely folded condition of the bordering Cretaceous and Cenozoic sedimentary formations in which the axes of folds on both sides trend slightly more east-west than does the fault. As the folds approach the San Andreas fault they become more severely compressed and their axes veer more nearly parallel to it. This persistent pattern all along the fault is no doubt the effect of right-lateral drag on the fault combined with the pressure of one block against the other.

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Train of the North Shore Railway at Point Reyes Station, Marin County. Engine and cars were overturned by the April 1906 earthquake. From the collection of Roy D. Graves.

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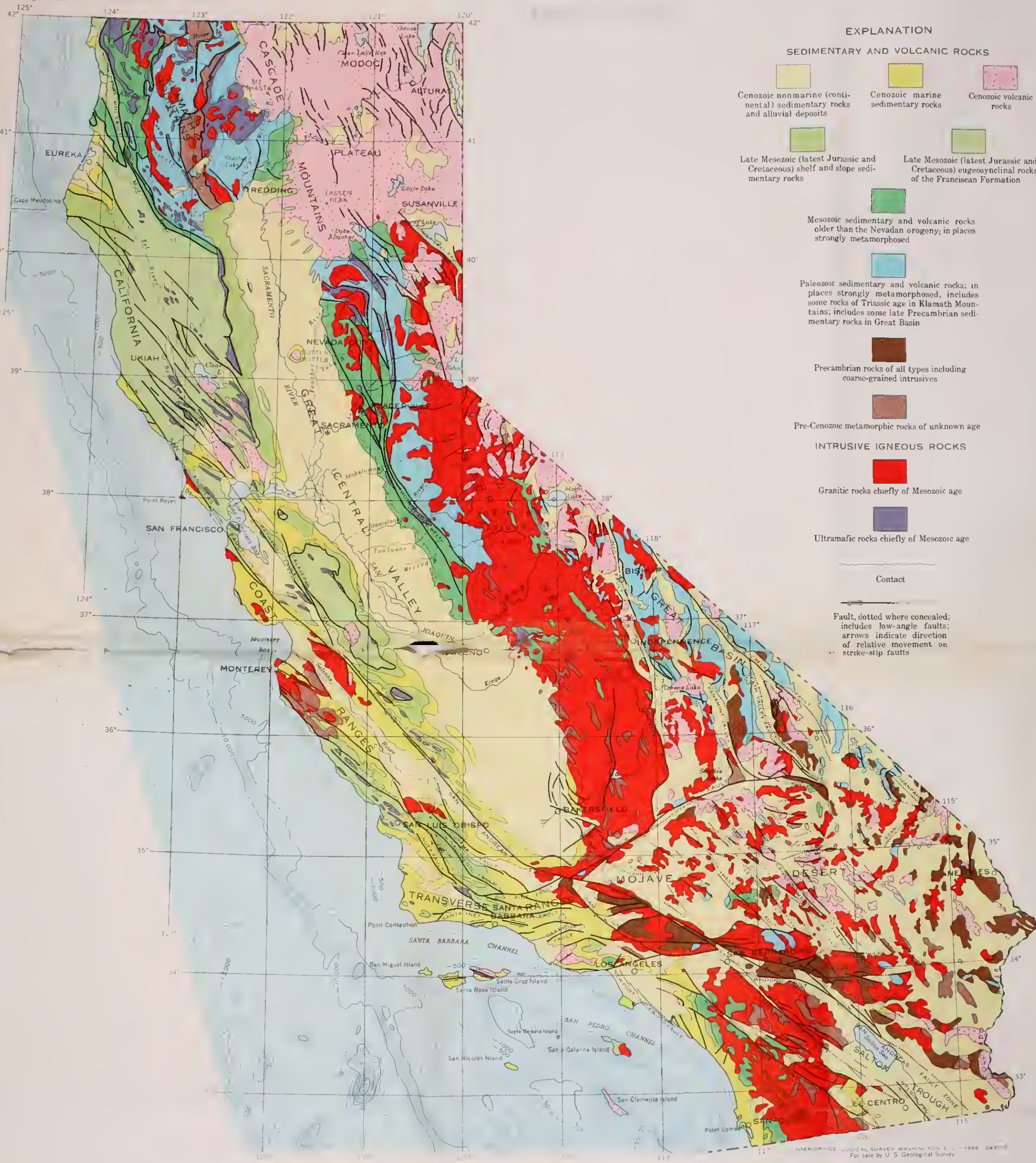
UNITED STATES GEOLOGICAL SURVEY

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