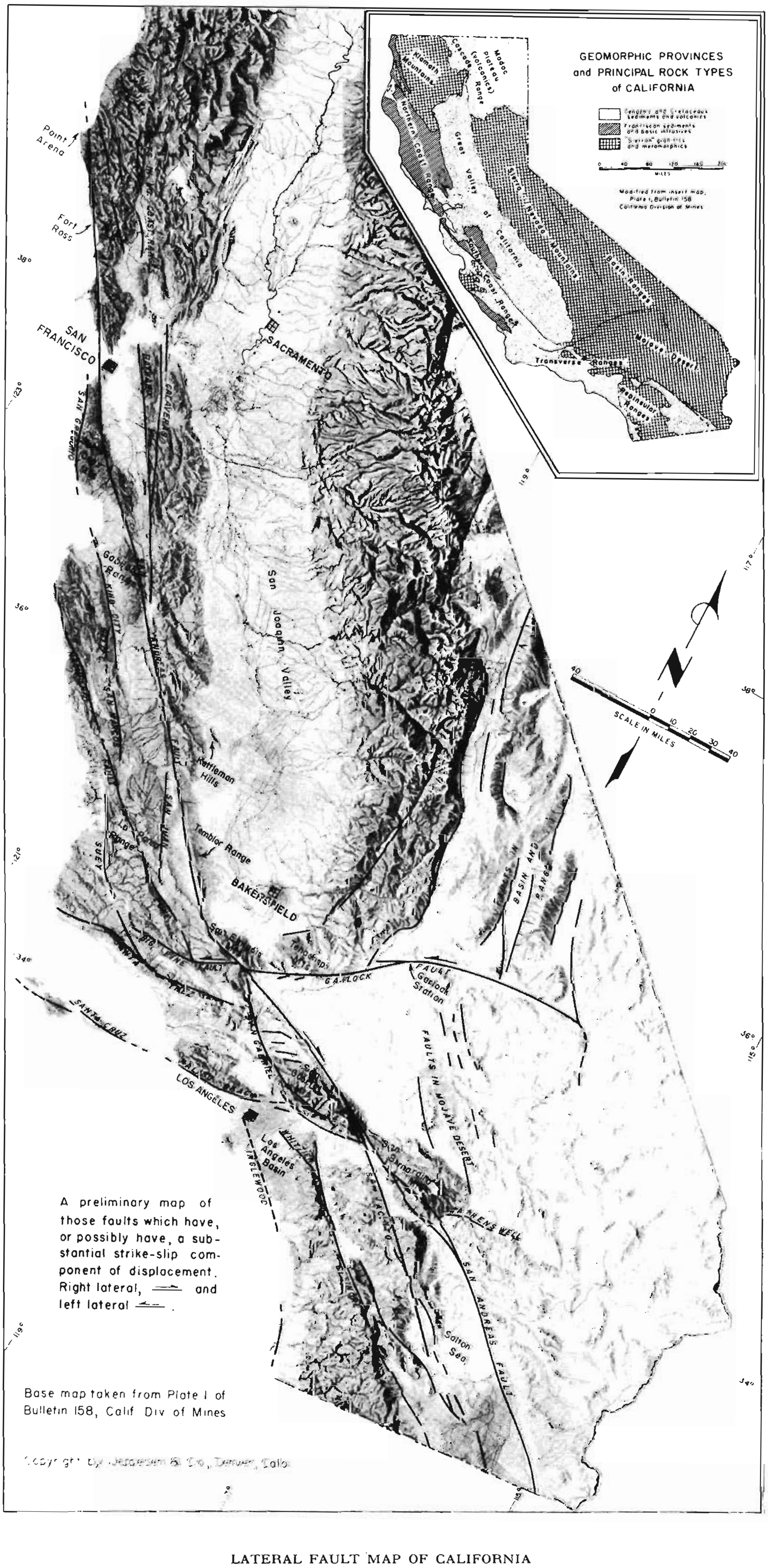

LATERAL FAULT MAP OF CALIFORNIA

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SAN ANDREAS, GARLOCK, AND BIG PINE FAULTS, CALIFORNIA

A Study of the Character, History, and Tectonic Significance of their Displacements

By Mason L. Hill and T. W. Dibblee, Jr.

Abstract

The Big Pine left lateral fault extends northeastward from Big Pine Mountain to the right lateral San Andreas fault, while the left lateral Garlock fault extends northeast from the San Andreas, but from a point 5 miles to the southeast. The Big Pine fault is considered the western segment of the Garlock fault as offset by the San Andreas. Movement on this Garlock-Big Pine fault zone appears to have caused the anomalous east-west trend of the San Andreas fault in this vicinity.

Tens of miles of lateral movement have probably occurred on these faults with the possibility of a cumulative movement on the San Andreas of hundreds of miles since Jurassic time. Such distances are important elements in reconstructing paleogeologic conditions.

The three concurrently active, long, steep, and deep faults are considered major conjugate shears which define a primary strain pattern of relative east-west extension and north-south shortening of an area of approximately 120,000 square miles. A northeast-southwest counterclockwise compressive couple, possibly set up by drag due to the deep-seated movement of rock material from the Pacific region, is tentatively postulated as causing the deformation in this large region.

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Introduction

Recent work shows, contrary to previously published maps, that the Big Pine fault, on the south slope of Big Pine Mountain, extends northeastward to the San Andreas. This work was done by the junior author (Dibblee) in 1947, on photographic and topographic base maps, as part of an oil-exploration program. The characteristics of the fault were recognized as possibly of regional tectonic significance which stimulated further studies by Dibblee and Hill (1948) upon which this presentation is founded.

The first part of the discussion presents evidence on the character and amount of the displacements of the faults with particular emphasis on interpretations of the history of the San Andreas fault; the second part deals with interpretations of relationships between these faults and their bearing on some other structural features of the region; and the third part analyzes the mechanics of the deformation and timidly suggests some genetic concepts and conclusions.

Most of the facts concerning the faults discussed are generally known, but some new data and interpretations lead to conclusions, particularly concerning the San Andreas fault, that are not now orthodox. These conclusions are mainly tentative and are offered for the criticism of other workers.

Acknowledgment is made to the Richfield Oil Corporation, for permission to publish, and to A. O. Woodford, Duncan A. McNaughton, John C. Crowell, Rollin Eckis, John Shelton, and John H. Wiese for criticism of the manuscript.

San Andreas Fault

Problems

This great Right Lateral[1] fault became widely publicized after the San Francisco earthquake of 1906. At that time a maximum of 21 feet of right lateral offset occurred on the San Andreas fault (Lawson, 1908). Much geologic study has since been devoted to this fault, and it has been mapped from Point Arena southeastward almost to Mexico, a distance of about 600 miles; however, the history of its displacements is still controversial. After nearly 50 years of research, workers disagree in their answers to the following questions:

1. What is the San Andreas fault?

Noble (1933, p. 11 says:

"It is marked by a curiously straight and almost continuously traceable chain of scarps, ridges and trough-like depressions.... This line of recent topographic features upon the San Andreas fault is commonly referred to as the fault trace. Bordering the fault is a belt of roughly parallel branching and interlacing fractures which at some places attains a width of several miles. This belt, the San Andreas fault zone, is a mosaic of elongated sliver-like blocks or wedges whose longer axes trend parallel with the main fault, so that the dominant structure is a sort of slicing...."

On the other hand, Taliaferro (1943, p. 160) says:

"Nearly everywhere along the San Andreas there is abundant physiographic evidence of recent faulting, such as true sag ponds and offset ridges and drainage lines. However, along the earlier mid-Pleistocene faults (which the San Andreas partially follows) there is no similar direct physiographic evidence of faulting.... It (the San Andreas) has produced no important modifications of either the structures or topography formed by these (earlier) diastrophisms.... The supposed branches or 'barbs' are actually earlier faults which were formed by a very different type of movement and which may be traced across the San Andreas."

2. What is the age of the San Andreas fault? All workers agree, on the firm basis of earthquake activity and topographic expression, that this fault is active. However, there is a distinct difference of opinion, in respect to its antiquity.

Noble (1933, p. 11) says:

"The fault is a very old line of weakness, upon which movements have recurred through Tertiary and Quaternary time and perhaps through much of pre-Tertiary time."

Taliaferro (1943, p. 161) contends that the San Andreas fault had its inception in late Pleistocene time and that it, with its unique characteristics, should not be confused with the older faults which are followed, and occasionally crossed, by the San Andreas.

3. What is known about the orientation (sense) of displacements of the San Andreas fault? All authors have agreed that the latest movements have been actually strike-slip with the southwest block relatively moving to the northwest (right lateral), but here again agreement stops. Those workers who believe that the San Andreas is an old fault differ in opinion on the relative importance of vertical and lateral components of these earlier movements. Most authors, for example Buwalda (1926), Clark (1929), Weaver (1949), and Willis (1929), believe that these earlier movements were predominantly vertical and that reversals of throw have taken place on this and parallel faults.

[1] The block opposite the observer, as viewed in horizontal section, is offset to the right (Hill, 1947). The terms *right* and *left lateral* are as critical in fault nomenclature as *normal* and *reverse*; they are descriptive of *separation* rather than definitive of *slip*; they are geometric rather than generic; and they are becoming widely used. Some English workers (Anderson, 1942, p. 55) use *dextral* and *sinistral transcurrent* for these types but with a *slip* instead of *separation* connotation.

4. Does the San Andreas fault zone mark a prominent contact between unlike rocks?

Noble (1933, p. 11–12) says:

"The profound difference in the rocks on opposite sides of the San Andreas fault shows that the fault movements have been of great magnitude.... Nowhere in the 30 mile sector (north side of San Gabriel Mountains) are the rocks on opposite sides of the fault similar."

Taliaferro (1943, p. 160) says:

"The San Andreas fault, however, is rarely the boundary between these two very diverse types, but usually is either wholly within crystalline (granitic) rocks or Mesozoic (Franciscan) rocks, except where it cuts through either Miocene, Pliocene or Pleistocene sediments."

5. What is the order of magnitude of the cumulative offset on the San Andreas fault?

Noble (1925–1926, p. 420) says early Tertiary strata may have been offset by the San Andreas (in a right lateral sense), a total distance of approximately 24 miles.

Taliaferro (1943, p. 161) says:

".... The horizontal shift (on the San Andreas) has been small, and has not been greater than one mile and probably even less."

The present authors believe that: (1) the San Andreas is a steep fault zone of variable width consisting of one or several nearly parallel faults; (2) its inception was quite likely pre-Tertiary, and it is now active; (3) it has probably been characterized by right lateral displacements throughout its history; (4) it marks such an important contact that rarely can it be crossed, except in Recent alluvium, without passing into significantly different rocks; and (5) its cumulative displacement of some rock units is at least tens of miles, and older rocks may have been displaced a few hundred miles.

Description and Interpretations

The San Andreas fault is so long that no one worker can have a first-hand detailed knowledge of its characteristics throughout its length. The junior author, however, has mapped a 100-mile stretch of the fault and associated geology in the Salton Sea region and most of the 300-mile stretch from the San Emigdio Mountains to San Francisco. This work and available maps and discussions by others are used in the following outline of significant fault characteristics and their bearing on the history of the San Andreas fault.

1. The trace of the San Andreas zone is typically continuous and straight (Pl. 1). Topographic and geologic features clearly show its continuity for about 600 miles. There is evidence of recent activity along its entire course. Excepting a 30-mile segment trending eastward in the San Emigdio Mountains, and another stretch of similar trend 100 miles to the southeast, the zone is remarkably straight from Point Arena southeastward nearly to Mexico. These aspects of continuity and straightness are considered typical of strike-slip faults.

2. The San Andreas is a steep fault which transects major topographic features but develops all along its course one or several parallel trenches, sag ponds, low ridges, saddles, and/or scarps. Its steepness is indicated by the straight trace, the fact that mapped fault planes are nearly vertical, and the failure of near-by drill holes to penetrate the zone. These characteristics are typical of strike-slip faults. The development of fresh topographic features, many of which are in unconsolidated recent sediments, and the common lack of appreciable vertical or consistent vertical components of offset clearly indicate the recency of lateral movements. Seismic evidence for recent right lateral movements on the San Andreas, as summarized by Wallace (1949), comprises the following maximum displacements at the time of earthquakes: 30 feet (San Emigdio Mountains, 1857), 10 feet (San Francisco area, 1868), 21 feet (San Francisco area, 1906), and 10 feet (Salton Sea area, 1940). Geodetic surveys in the San Francisco (Whitten, 1948) and Salton Sea (Meade, 1948) areas also show this type of recent movement.

3. The San Andreas fault zone ranges from a few feet to a few miles in width. Locally a single recent trace may be irregular, with 15-degree variations in strike within a few hundred feet, or it may disappear and be replaced, en echelon, by another. Occasionally two or three parallel traces widen the zone of recent traces to a maximum of about half a mile. Wider segments of the zone consist of several faults (not necessarily active) which are usually steep and nearly parallel to the trend of the zone. These

characteristics are considered typical of strike-slip fault zones along which recurring movements have taken place.

4. The apparent throw is commonly reversed along the San Andreas fault as indicated by topographic and geologic relationships. These throws are probably due to the major strike-slip component which places in juxtaposition unlike topographic elevations and geologic sections, and thus the reversals of dip-slip are mainly illusory.

5. Drainage lines are consistently offset in a right lateral sense. These offsets are especially clear on the southwest side of the Temblor Range (Fig. 1) where a maximum of 3000 feet of displacement has occurred through recent movements on the fault. Wallace (1949, p. 805) reports a probable drainage offset of 1½ miles on the north side of the San Gabriel Mountains, and Allen (1946, p. 50) reports 3800-foot offsets of drainage lines near the Gabilan Range, also in a right lateral sense.

6. Recently developed trenches which trend southward into the fault have been observed in aerial reconnaissance on the southwest side of the Temblor Range. These are oriented correctly to be tensional in origin and due to right lateral movement on the San Andreas.

7. Locally developed west-northwest trending folds adjacent to the San Andreas are obviously drag folds resulting from the right lateral movement on the San Andreas. Such drag folds are especially clear in the Salton Sea Region, and, besides indicating the right lateral sense of movement on the fault, many of them show by their discordance with topographic form that the fault was active before the present physiographic features were developed.

8. Wallace (1949) reports a probable 6-mile right lateral offset of terrace deposits on the north side of the San Gabriel Mountains, and L. F. Noble (personal communication) describes similar late offsets in that area of several miles.

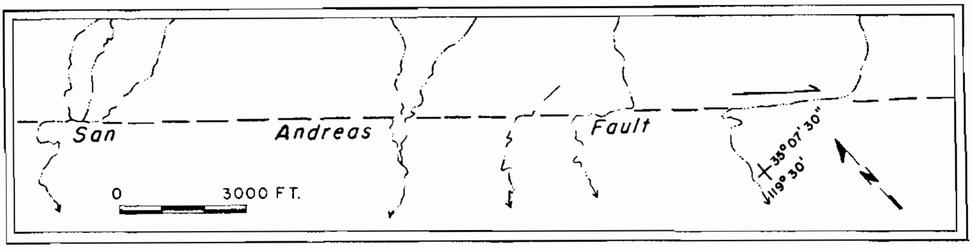

FIGURE 1.—RIGHT LATERAL OFFSET OF DRAINAGE LINES BY THE SAN ANDREAS FAULT
Elkhorn Hills quadrangle

9. Between the San Emigdio Mountains and the Temblor Range, there are two facies of Pleistocene gravels. On the southwest side of the San Andreas, the pebbles are granite, gneiss, quartzite, limestone, black shale, and sandstone which undoubtedly came from the San Emigdio Mountains. On the other side of the fault, the pebbles are almost exclusively white siliceous shale which probably came from the Miocene shale of the Temblor Range. These two facies are in direct contact along the San Andreas for several miles. Furthermore, the northwest end of the crystalline clast facies is about 14 miles northwest of the crystalline rocks of the San Emigdio Mountains. These relationships thus indicate a right lateral displacement of approximately 10 miles on the San Andreas fault since Pleistocene deposition in this area (Fig. 2).

10. In the Caliente Range, marine sediments of upper and middle Miocene age grade laterally eastward into continental red beds which strike into the San Andreas fault, whereas strata of the same age are marine shales on the other side of the fault. This juxtaposition of unlike facies again demonstrates substantial lateral movement. In this case the general trend of the western margin of the continental facies in the Caliente Range is northward across the Carrizo Plain toward the San Andreas, whereas possibly the same transition line may be extrapolated southward from along the east side of the San Joaquin Valley to the fault. Thus, by simple projections the right lateral offset on the

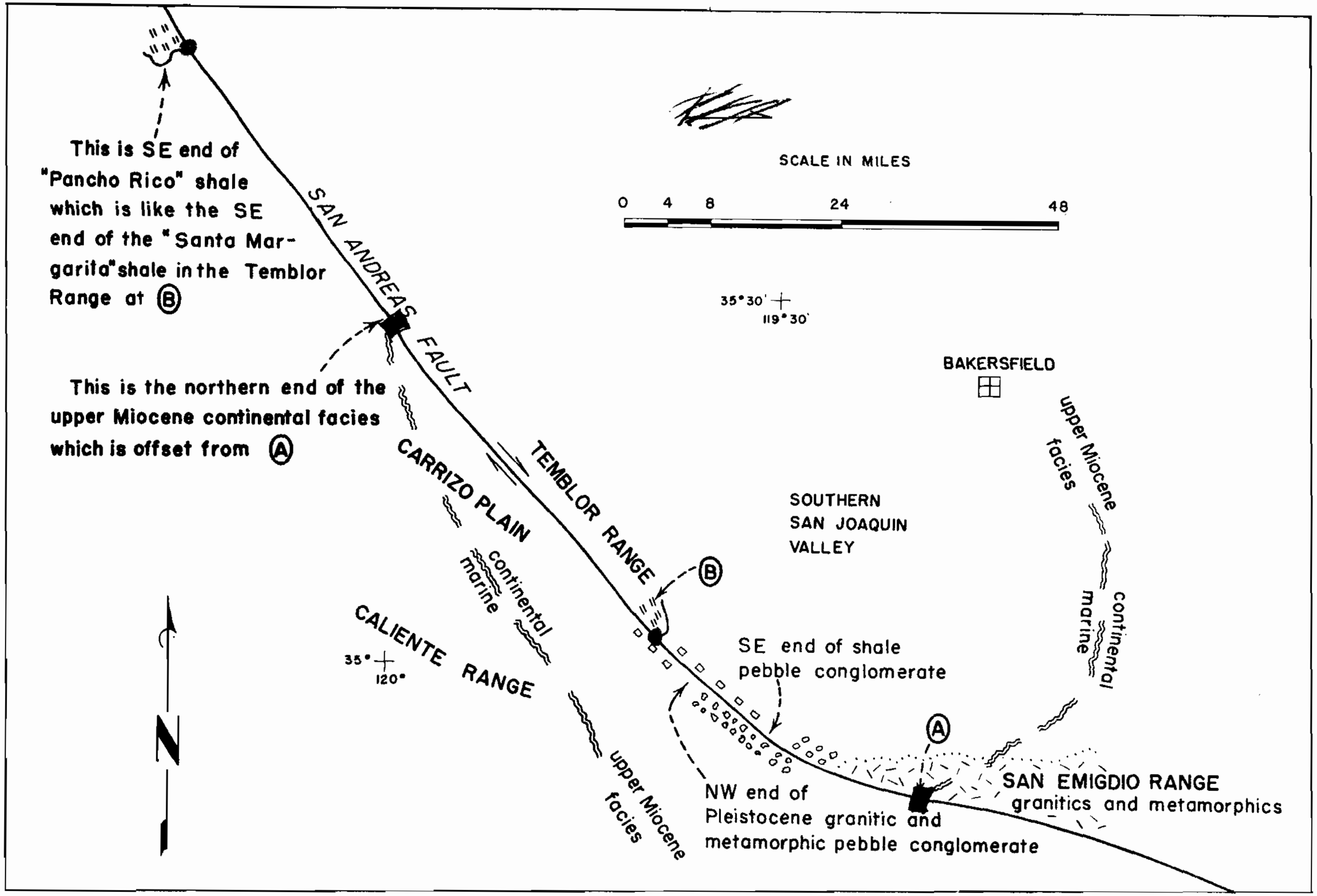

FIGURE 2.—OFFSETS OF PLEISTOCENE AND UPPER MIOCENE FACIES BY THE SAN ANDREAS FAULT

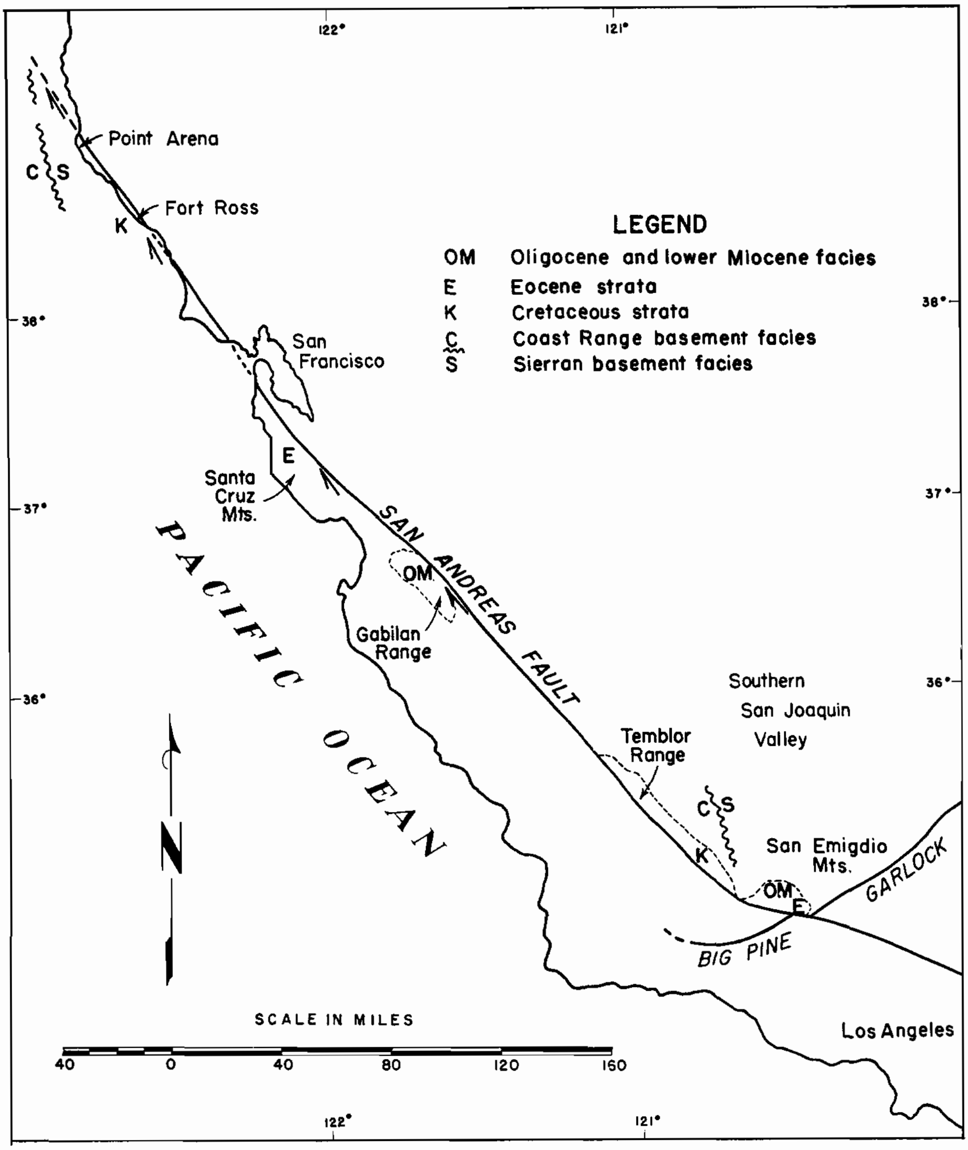

FIGURE 3.—POSSIBLE OFFSETS ON THE SAN ANDREAS FAULT SINCE JURASSIC TIME

These time-rock facies appear to be offset from the southern San Joaquin Valley area to the positions indicated on the west side of the fault. Thus, for example, during Cretaceous time the Fort Ross section may have been adjacent to the Temblor Range section.

fault since upper Miocene time would be about 65 miles, although the probability of irregularities in trend of this facies contact precludes a strictly quantitative solution of that cumulative shift (Fig. 2). Note the comparable offset of the upper Miocene "Pancho Rico"-"Santa Margarita" shale, shown in the same figure.

11. Going back only slightly farther in the geologic record, approximately 175 miles of right lateral offset may have accumulated on the San Andreas fault since early Miocene time. This is suggested by the unique similarities of rock types and sequences in the San Emigdio Mountains, as described by Wagner and Schil-

ling (1923), and the Gabilan Range as described by Kerr and Schenck (1925), and Allen (1946). In each of these areas, a section of lower Miocene volcanics, red beds, and marine lower Miocene and Oligocene strata occurs (Fig. 3).

12. A similar relationship is suggested by some lithologic and faunal similarities between the Eocene formations of the Temblor-San Emigdio and the Santa Cruz Mountains which indicate the possibility of an offset of approximately 225 miles since late Eocene time (Fig. 3).

13. Also the southern limit of Cretaceous strata in the Temblor Range may match with the southern limit of Cretaceous beds near Fort Ross which would indicate an offset of approximately 320 miles (Fig. 3). This possibility is strengthened by the improbability that vertical movements were consistent enough to remove the Cretaceous strata from such a long belt on the southwest side of the San Andreas fault zone. Furthermore, the Cretaceous sediments which do occur as close as 12 miles southwest of the San Andreas in the La Panza Range (Pl. 1) are west of other important faults and rest on granitic instead of Franciscan basement.

14. Of great interest would be good evidence for offset of the pre-Cretaceous rocks by the San Andreas. Perhaps the southward-trending contact between the Sierran complex and the Coast Range Franciscan complex which is concealed by the sediments of the Great Valley is truncated by the fault in the southern Temblor Range with its offset equivalent concealed by the sea north of Point Arena. This would amount to at least 350 miles of right lateral displacement since Jurassic time (Fig. 3).

Discussion and Conclusions

The antiquity and amount of movement on the San Andreas fault is evidenced by the increased offset of older rock facies as matched across the fault zone. The possibility of a pre-Cretaceous age and a cumulative right lateral displacement of several hundred miles is thereby suggested. These conclusions are both speculative and qualitative but tenable enough to justify further critical work to test their correctness and to determine more exactly their values. There is, however, no reasonable doubt that the fault is at least as old as early Pliocene and that the total right lateral offset is at least tens of miles (Figs. 2, 3).

Of perhaps great significance is the increased offset of older rock facies on the west side of the San Andreas from their probable counterparts at the southern end of the San Joaquin Valley (Fig. 3). This situation appears to indicate that one block was actually moving past the other. If this were not true the counterparts would also be progressively shifted in the opposite direction. A conclusion regarding this movement will be presented under the subject heading of "Mechanics of the faulting."

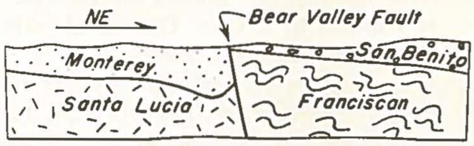

FIGURE 4.—SKETCH SECTION ACROSS THE BEAR VALLEY FAULT

After Wilson (1943, p. 227)

Those workers who maintain that the San Andreas refers only to a fault which has been active recently and which had its inception in late Pleistocene time and those others who believe in earlier dip-slip and reversals of dip-slip displacement on the San Andreas may be skeptical of these conclusions. However, these differences in opinion appear to result from definitions of the fault and interpretations of displacement from cross-section relationships. The present authors believe that: (1) in many places the San Andreas is a wide zone comprising several important faults which are parallel or nearly parallel to the recent trace, and (2) the apparent dip-slip displacements are mainly the result of substantial lateral movements which put unlike geologic sections in juxtaposition.

The Bear Valley fault, east of the Gabilan Range (Wilson, 1943, p. 251), illustrates these differences in opinion and interpretation. This fault is mapped about half a mile southwest of the recent trace of the San Andreas and dips steeply northeast. It separates middle Miocene (Monterey) sediments resting on the Santa Lucia granite on the southwest side from a section of Plio-Pleistocene (San Benito) gravels resting on the Franciscan complex (Fig. 4). Wilson's interpretation is that this "ancestral"

San Andreas fault is not the San Andreas because it shows no evidence of recent movement, it is not vertical, and it is supposed to be characterized by dip-slip rather than strike-slip displacement. According to Wilson the first movement, probably Eocene normal faulting, elevated the west side causing the Franciscan to be removed by erosion. The second period of movement was post-Miocene, and, by reverse faulting, the east side was elevated with accompanying erosion of all the Miocene strata on that block. The third period of movement occurred in late Pleistocene or Recent times as normal faulting which again elevated the west block causing the removal of the San Benito gravels.

The present authors suggest, based on the same data and by pinning a little faith on the law of uniformitarianism, the following tentative interpretations:

The juxtaposition of granitic and Franciscan basement may be the result of a great many miles of cumulative lateral movement on the fault. The absence of Miocene sediments on the northeast side of the fault may be due to many miles of right lateral movement so that the facies of the southwest block in this area were offset far to the southeast. The absence of the Plio-Pleistocene gravels on the southwest side of the fault in this area may also be due to right lateral offset with the possibility that they could be found several miles to the northwest on that side of the San Andreas. Although no recent movement has occurred on the Bear Valley fault, it is probably an inactive and slightly deformed fracture within the San Andreas zone which was characterized by the same type of movement as is evidenced along the recent trace of that fault.

It appears then that the significance of the Bear Valley fault is debatable. It is discussed here only as an example. An alternate interpretation is suggested in order to focus attention on a possibility that seems to have been overlooked. If the Bear Valley fault or other structures similarly related to the San Andreas, such as the Pilarcitos fault in the San Francisco area, can be shown to effect substantial right lateral offset, it will be reasonable to include them in the San Andreas fault zone as a partial manifestation of the important history of that zone. Furthermore, it would eliminate the not too probable interpretations of reversals of dip-slip displacements from cross-section relationships and the postulation of a unique and new strain-stress environment to explain the recent trace of the San Andreas fault.

The type of evidence used in this paper for the cumulative offset on lateral faults is not wholly new, nor are the suggested offset distances unprecedented. Kennedy (1946) has demonstrated 65 miles of strike-slip displacement on the Great Glen fault in Scotland, and the Alpine fault in New Zealand may have 300 miles of lateral displacement according to Wellman (1949 and personal communication). Even in California Vickery (1925) determined that the relatively minor Sunol (Calaveras) fault has had 13 miles of right lateral displacement since early Miocene time by what appears to be a unique match of strata across this fault. Furthermore, the cumulative amount of lateral movements, which are tangential to the earth's surface, need not be as limited as for high-angle dip-slip faults which are necessarily limited by gravitational forces.

Much more work is obviously needed to verify qualitatively some of these tentative conclusions. Many more possible offsets must be analyzed for accuracy and compatibility with respect to geologic time and geographic distribution before sound quantitative conclusions can be reached. In general, the younger rocks should be more easily matched across the fault, but the offsets of older units, particularly the pre-Cretaceous crystalline rocks, will be more significant. For example, is the north end of the Pelona schist on the north side of the San Gabriel Mountains (Wallace, 1949) offset 160 miles from the north end of the Orocopia schist near the Salton Sea (Miller, 1944)? Then, is such an offset commensurate with the pos-

Plate 2. SAN ANDREAS, GARLOCK, AND BIG PINE FAULTS

Figure 1. Termination of Big Pine Fault at the San Andreas

View north

Figure 2. Trenches Adjacent to Garlock Fault

FIGURE 1

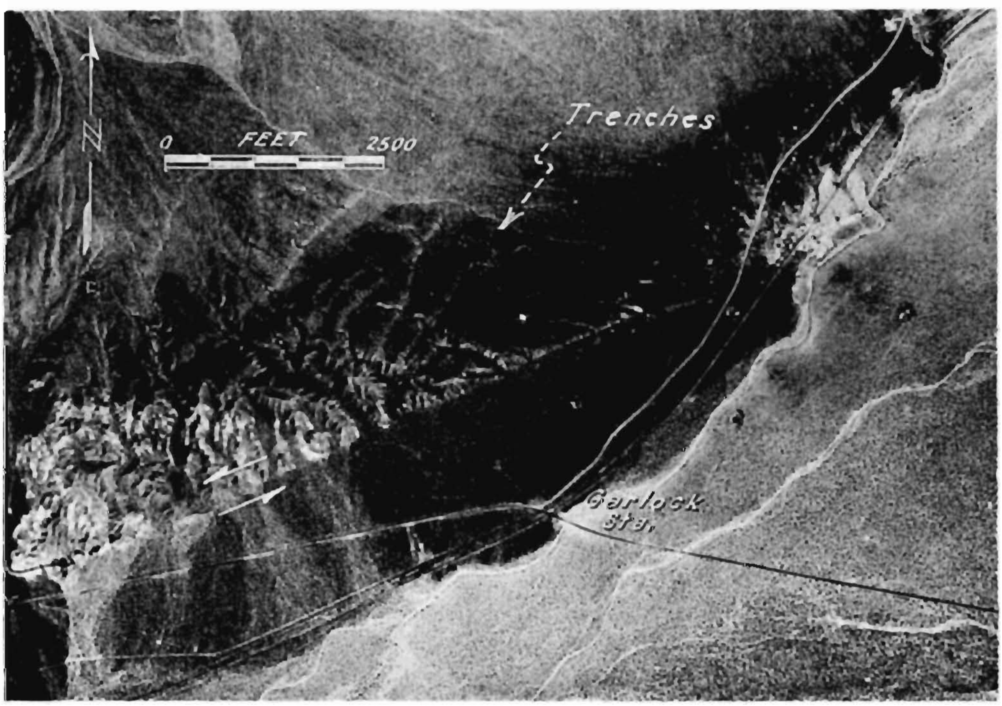

FIGURE 2

SAN ANDREAS, GARLOCK, AND BIG PINE FAULTS

FIGURE 1

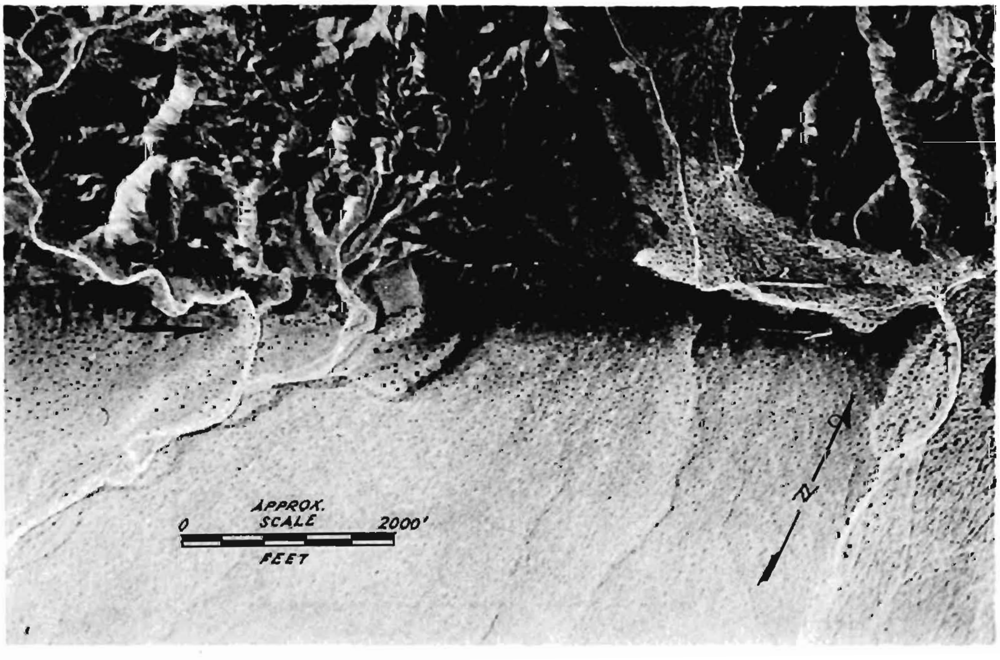

FIGURE 2

GARLOCK FAULT

sible offset on the San Andreas north of the Garlock-Big Pine fault zone?

Another worth-while line of research is the study of rates of movement on the San Andreas fault. Geodetic work has demonstrated a right lateral movement in the San Francisco Bay region averaging 2 inches a year since the survey of 1880 (Whitten, 1948). Another method, based on offsets at the time of earthquakes, suggests an average movement along the entire length of the fault of about 0.2 inch a year since 1857 (Wallace, 1949). Now, from the probable and possible offsets described above and the available calculations of geologic time in years, the rates of movement come out in fractions of an inch per year, as follows: 0.25 since Miocene, 0.2 since lower Miocene, 0.3 since Eocene, 0.29 since Cretaceous, and 0.2+ since Jurassic time. These figures are surprisingly consistent and therefore may possibly be taken as evidence that the rate of movement has been rather uniform for some 100 million years. On the other hand, the geodetically determined rate is nearly tenfold greater than these geologically controlled figures. However this great rate might be anomalous because of the short time involved, the short length of the fault involved, the inclusion of the large displacement of 1906, and/or movements outside the fault zone.

Garlock Fault

The Garlock fault extends from the San Andreas northeast and east-northeast for 150 miles (Pl. 1). It, like the San Andreas fault, transects topographic features, dips steeply, and has apparent variations of throw along its course.

Hess (1910, p. 25) first described and named the fault and indicated its type locality as just north of Garlock Station. Hulin (1925) was the first to suggest lateral displacement. He used the offset of a contact as possible evidence for left lateral displacement of approximately 6 miles.

The present authors followed this fault zone from its junction with the San Andreas northeastward for 150 miles by airplane and saw many well-defined offsets of drainage lines. These are all in a left lateral sense and commonly a distance of 2000 feet (Pl. 3). Also seen on this air reconnaissance were trenches in old alluvium in the vicinity of Garlock Station, immediately north of the fault trace (Pl. 2, fig. 2). These parallel trenches, approximately 40 feet deep, 150 feet wide, and 2000 feet long, trend S. 30°W. into the N. 60°E. trending Garlock fault trace. Their characteristics, including orientation and proximity to the Garlock fault, suggest gash fractures produced by tensional stresses adjacent to a major shear zone.

These striking evidences of recent and actual left lateral movement have, surprisingly, not hitherto been emphasized in the geologic literature. However, Wiese and Fine (1950, p. 1652) report at least 2 miles of left lateral offset on the Pinon Hill fault (a subparallel branch of the Garlock on the south side of the Tehachapi Mountains), and D. F. Hewett (1950) describes new evidence for recent offset on the Garlock fault zone east of Garlock Station. Thus the sense and recency of movement on this great fault are considered firmly established. The time of initiation and the total amount of left lateral offset on the Garlock fault are not yet known.

Big Pine Fault

Nelson (1925, p. 379–380) first mapped and described the Big Pine fault as it occurs on the south side of Big Pine Mountain. He sketchily mapped the fault from here some 15 miles eastward. Later, Reed and Hollister (1936, p. 94–96) extended the fault to the southeast, as it is likewise shown on the Geologic map of California (Jenkins, 1938). The present mapping shows that this southeastward extension is in error, but that the fault does extend in a clearly revealed trace northeastward to the San Andreas (Pl. 2, fig. 1). Now it is evident that Nelson's east-west portion of the fault and this

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Plate 3. GARLOCK FAULT

Figure 1. Left Lateral Offset of Drainage Lines

Seven miles northeast of Garlock Station.

Figure 2. Left Lateral Offset of Drainage Lines

Ten miles northeast of Garlock Station.

newly mapped and equally long northeast-trending portion gives the Big Pine fault a length of 50 miles and establishes it as a major fault of the region.

The extended portion of the fault trends N. 65°E., with steep dips varying from north-

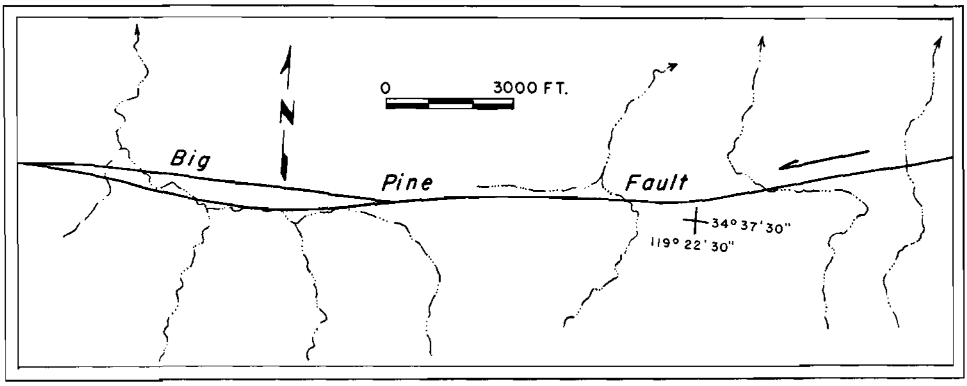


FIGURE 5.—LEFT LATERAL OFFSET OF DRAINAGE LINES BY THE BIG PINE FAULT
Morro Hill and Reyes Peak quadrangles

west to southeast and with the throw apparently reversing along its course. At its type locality,[2] 9 miles southwest of Mt. Pinos, the fault separates Miocene continental beds from Eocene marine strata to the south (Pl. 4). Here the fault strikes N. 60°E. and dips 70°S. Striations have been found on slickensided planes of the fault zone which are 70° clockwise from the direction of dip.

This left lateral fault has a prominent strike-slip component of displacement as indicated by the following field observations:

1. The oblique-slip striations in the fault zone indicate a predominant strike-slip component of displacement and their orientation combined with the orientation of apparent throw indicates that the southeast side has moved northeastward and up the 70-degree fault plane. On this evidence alone the fault should be classified as a "left lateral reverse," but, since reversals of dip and apparent reversals of throw occur along the fault trace, the appearance of reverse faulting at the type locality is not significant.

2. Left lateral offsets of drainage lines along the Big Pine fault indicate the sense and recency of displacements. Figure 5 shows three such offsets, two of which are displaced approximately 3000 feet.

3. East-west trending drag folds adjacent to the Big Pine fault indicate left lateral displacement (Pl. 4).

4. Left lateral offset of approximately 8 miles since Miocene time is suggested by the possible displacement of a major syncline and a northwest-trending fault contact between Eocene and Miocene strata (Pl. 4).

5. The continental facies of the Miocene, together with its fanglomeratic members extends farther west on the north side of the Big Pine fault than on the south side (Pl. 4).

6. A well 14 miles southwest of Mt. Pinos and just north of the fault (Pl. 4) encountered continental Miocene conglomerate on granitic basement which matches a similar sequence on the south side of the fault 14 miles to the east.

The time of initiation of the Big Pine fault is unknown, but its age must be substantial, considering the probable minimum cumulative displacement of approximately 8 miles.

RELATIONSHIPS OF THE FAULTS

The more important aspects of the San Andreas, Garlock, and Big Pine faults, for the present analysis, are as follows:

1. The faults are essentially contemporaneous, as attested especially by the recency of their displacements.

2. The faults are major structures of the re-

[2] A type locality is picked as recommended by Buddenhagen *et al.* (1930).

gion, as attested by their great lengths and probable great cumulative displacements.

3. Of the three fault zones, the San Andreas is dominant, and its trend predominates in the regional faulting. However, the Big Pine and subparallel Santa Ynez faults separate the northwest-trending Coast Ranges from the east-west trending Transverse Ranges, and the Garlock fault separates the Basin and Range region from the Mojave Desert province.

4. The Big Pine and Garlock faults are on the same trend and are alike in the character of their displacements, as attested by the evidence for left lateral movement on each.

5. The San Andreas right lateral fault zone intersects, at a substantial angle, the Garlock-Big Pine left lateral fault zone.

Based on these data, the more important relationships between the faults appear to be as follows:

1. The Big Pine fault is probably the offset extension of the Garlock fault since its essential characteristics are the same as the Garlock, since it is the only major left lateral fault in the area, and since it abuts the San Andreas at a point northwest of the west end of the Garlock fault, as is consistent with the right lateral movement on the San Andreas. Nolan (1943) expressed the opinion that the Garlock fault should be found about where the Big Pine fault is now mapped but to his knowledge it did not occur. He concluded that, if the Garlock fault did exist west of the San Andreas, it might be offset to the southeast and if so would indicate an anomalous (left lateral) movement on the San Andreas. Finding what was reasonably expected has fortunately then eliminated the possibility of an unlikely reversal of movement on the San Andreas. Furthermore, this shift of 5 miles is in accord with the 5-or 6-mile offset of terrace deposits by the fault 50 miles to the southeast (Wallace, 1949).

2. The big bend in the trace of the San Andreas, that east-west trending portion (Pl. 1), occurs where abutted by the Garlock and Big Pine faults. This anomalous trend is now readily explained by the left lateral movement on the Garlock-Big Pine fault zone. Even the total amount of roughly 25 miles of offset due to the bend is not, in the opinion of the writers, out of line with the possible amount of left lateral offset on the Garlock-Big Pine zone.

3. Another big bend of the San Andreas occurs in the San Bernardino Mountains, approximately 100 miles southeast of the bend described above (Pl. 1). Here possible left lateral movement on the "Warrens Well" fault may be responsible for this other anomalous trend of the San Andreas fault. Critical work on the "Warrens Well" fault would quite likely establish the merit of this inference.

4. Another speculation is that the San Gabriel fault (Pl. 1) is an ancestral portion of the San Andreas. This fault, which occurs south of the Big Pine, extends southeastward on trend with that portion of the San Andreas which lies north of the Big Pine fault. Thus the San Gabriel fault may have been the southeastern continuation of the San Andreas before the big bend was developed. The fact that, according to Crowell (1950), the San Gabriel fault shows evidence of less recent activity than the present San Andreas is a reasonable consequence of such a possibility. Along this line of thinking, the San Jacinto fault (Pl. 1) could be conceived of as also being an earlier representative of the San Andreas in this southern area. Thus the San Jacinto[3] fault would be younger than the San Gabriel fault and perhaps older (although still active) than the present trace of the San Andreas. Likewise the Calaveras and Hayward faults might perhaps be the earlier initiated manifestations of the San Andreas fault zone in the San Francisco Bay region (Pl. 1). It is further suggested that the cumulative right lateral displacement on this greater San Andreas fault system could be of a magnitude of several hundreds of miles. This concept is strengthened by Crowell's report (1952) of 15 to 25 miles of right lateral movement on the San Gabriel fault alone, and during a short interval of geologic time (between late Miocene and late Pliocene). Such a possibility is obviously shocking, particularly when considering its effect on paleogeographic maps which straddle this zone.

Substantiation of the interpretation that the Big Pine and Garlock faults comprise one fault zone is not necessary to the probability that the bend of the San Andreas is related to their left lateral movements or vital to the following

[3] Five miles of right lateral movement is indicated on the San Jacinto fault (Arnett, 1949), and the localization of Jurassic (?) alaskite dikes in the fault zone indicates its early origin (Sprotte, 1949).

analysis of the mechanics of the regional deformation. It is, however, essential that the Big Pine and Garlock once comprised one continuous fault if used as evidence of 5 miles of right lateral offset on the San Andreas. However, since the sense and magnitude of the displacement on the San Andreas from other evidence is compatible with this offset of the Garlock-Big Pine trend, the probability is that a continuous line of faulting actually did at one time exist. Also, the interpretations concerning the other big bend of the San Andreas or the possible historical connections between either the San Gabriel or San Jacinto faults and the San Andreas are not essential to the primary theses of this presentation.

Mechanics of the Faulting

Introduction

The geomorphology of California ranges from high precipitous mountains to low plains (Pl. 1). The larger so-called valleys are usually structural depressions (basins), and many are separated from the mountains by important faults. The geomorphic provinces are also usually geologic provinces, with the main mountain ranges characterized by highly deformed older sediments, metamorphic and plutonic rocks, and the basins characterized by thick, younger and less deformed sedimentary sections (Pl. 1, insert map). Although there are many exceptions, owing in part to the intense and wide-spread late Pleistocene tectonic activity, some of these geomorphic-geologic provinces have persisted through at least most of the Tertiary period, and therefore some of the bounding faults are probably of considerable age.

The principal rock types of California, classified according to characteristic response to deformational stresses, are as follows:

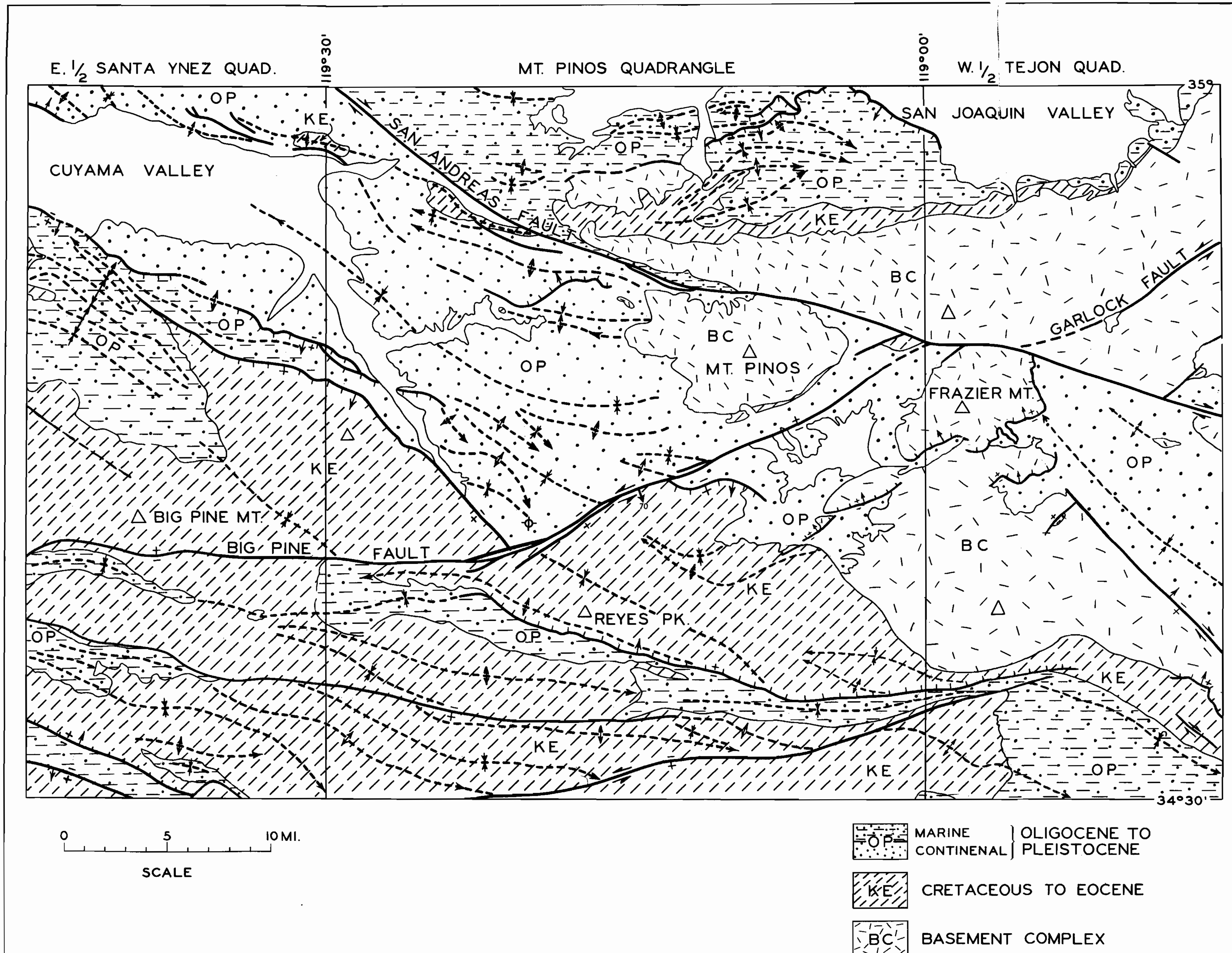
1. Sierran basement complex (pre-Cretaceous): metasedimentary and metavolcanic rocks, intensely deformed and widely invaded by granitic rocks. Because of physical similarity, the Santa Lucia granitics and metamorphics of the southern Coast Ranges and the complexes of the Transverse and Peninsular ranges belong in this group. These are relatively rigid rocks which fail locally by fracturing and, since they or rocks like them are extensively exposed and are presumably of state-wide occurrence at depth, their mechanical behavior is tectonically important.

2. Franciscan basement (pre-Cretaceous): sedimentary and volcanic rocks, regionally unmetamorphosed but highly indurated, commonly intruded by basic igneous rocks which are usually altered to serpentine and have caused local metamorphism. These rocks are exposed in large areas in the Coast Ranges; on the northeast side of the San Andreas fault, and also on the west side of the Nacimiento fault zone. They presumably underlie a much greater area but are probably in turn underlain by granitic rocks. The Franciscan, unlike the granitic basement, is typically incompetent. Although in places intensely fractured, often before being covered by later Jurassic or Cretaceous strata, and usually in fault contact with the other principal rock types, its response to deformational forces has been characterized by folding.

3. Cretaceous and Cenozoic sedimentary and volcanic formations: mainly marine clastic sediments with local volcanics and nonmarine deposits, not strongly lithified and of extremely variable thicknesses and facies. Deposited in large and small basins; locally highly deformed, especially during the late Pliocene-Pleistocene revolution in the Coast and Transverse Ranges, and in uplifts in the Mojave Desert and Salton Sea regions. These rocks form a pliable mantle on the above-described complexes and have therefore responded to tectonic forces primarily by folding, particularly where the sedimentary section is thick or where underlain by Franciscan basement.

The San Andreas, Garlock-Big Pine, and other similar faults are obviously at odds with the geomorphic-geologic provinces and the structural characteristics of the rock types of the region. The unique nature of these faults is shown by their transection of the geomorphic-geologic provinces and by their transection of all the principal rock types, without significant variations.

There are many important northwest-trending steep faults in California which are approximately parallel to the San Andreas, and which are probably also characterized by major right lateral components of displacement (Pl. 1). Several of these are present in the northern


E. 1/2 SANTA YNEZ QUAD.
119°30'
MT. PINOS QUADRANGLE
119°00'
W. 1/2 TEJON QUAD.
35°
34°30'
SAN JOAQUIN VALLEY
CUYAMA VALLEY
SAN ANDREAS FAULT
GARLOCK FAULT
BIG PINE FAULT
MT. PINOS
FRAZIER MT.
BIG PINE MT.
REYES PK.
OP
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5
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SCALE
MARINE
CONTINENAL
OLIGOCENE TO
PLEISTOCENE
CRETACEOUS TO EOCENE
BASEMENT COMPLEX

Coast Ranges, but they have not been described in detail. In the southern Coast Ranges, they include the Calaveras, Hayward, Pilarcitos, San Gregorio, San Marcos, Reliz Canyon, San Juan, and Suey faults, and the long Nacimiento fault zone; in the Transverse Ranges, the San Gabriel and San Jacinto faults; in the Los Angeles Basin, the Whittier and Inglewood faults; and, in the Peninsular Ranges, the San Jacinto and Elsinore faults. The several northwest-trending faults in the Mojave Desert and in the Basin and Range province, some of which are known to affect right lateral offsets, probably also belong in this group. The faults of this set are much more common than the east-northeast set of lateral faults.

The important east-northeast trending lateral faults which, like the Garlock-Big Pine zone, probably have significant left lateral displacements, include the Santa Ynez, White Wolf, possibly the Malibu Beach, faults in the northwestern portion of the San Gabriel Mountains, the "Warrens Well," and faults on Santa Rosa and Santa Cruz Islands. The faults of this set are most common in the Transverse Ranges. Other faults of both sets are quite likely present on the continental shelf.

Confusion should not exist, although it surely does, between these sets of steep lateral faults and those many other faults, both large and small, which indicate vertical relief or local adjustments due to secondary or superficially acting forces.

Large west-northwest trending thrust and reverse faults are especially common in the Transverse Ranges but they can, perhaps usually, be differentiated from the east-northeastward trending Garlock-Big Pine set by degree of dip and orientation of trend. Further confusion will undoubtedly likewise continue to exist between the thrust and reverse faults of the Coast Ranges and the San Andreas type faults. This is particularly true because superficially and locally acting forces are certain to modify the dips and strikes of the steep northwest-trending right lateral faults.

Strong folding of Cretaceous and Cenozoic strata is very common in both the Coast and Transverse ranges. In the Coast Ranges, the main folds and associated faults typically trend a little westward from the northwest San Andreas trend. In the Transverse Ranges, the main fold axes typically trend a little north of west in contrast to the east-northeast trend of the Garlock-Big Pine set and again the major thrust and reverse faults are approximately parallel to the folds.

It is here hypothesized that the folds and accompanying thrust and reverse faults of the Coast and Transverse ranges are shallow structures compared to the steep, and surely deep, lateral fault system. This concept furthermore suggests that these folds and faults which affect upward relief are secondarily related to the deep-seated forces which presumably developed the lateral fault system of nearly horizontal relief. Other minor faults and folds of diverse trends are even less directly related to the primary regional forces. As an example, the Kettleman Hills anticline of the southern Coast Ranges is a minor structure compared to the San Andreas fault zone, but the faults on it are still more local and superficial and thus more remotely related to the regional tectonic forces.

To ascertain the orientation of deformational forces which develop even minor structures is fraught with difficulties, but in such analyses, based on good mapping and sound principles of mechanics, lies the possibility of taking the Coast Ranges of California out of the defeatist category of a "heterogeneous mobile belt".

Strain Pattern ✓

Since the Garlock-Big Pine and San Andreas fault zones are the major fracture features of the region, and since they are concurrently active, they are probably genetically related. Then since the displacements of these intersecting fault zones show a systematic relative east-west extension and north-south shortening, their common origin seems to be an inevitable conclusion. Therefore, these fault zones are considered to comprise a "strain pattern" or system which is the result of a particular set of deforming forces.

This strain pattern is considered to be the primary fracture system of the entire region because these are the long faults (measured in hundreds of miles); they are deep faults (at least 10 miles as indicated by the usual calculated depth of foci of earthquakes in this region); and they are probably the faults of maximum cumulative displacement. Other large faults such as the San Gabriel, Nacimiento, and Santa Ynez (Pl. 1) may be nearly as directly related to the primary regional stresses, but the multitude of smaller faults and folds are undoubtedly in secondary or tertiary order strain systems which are only indirectly related to the primary stress pattern.

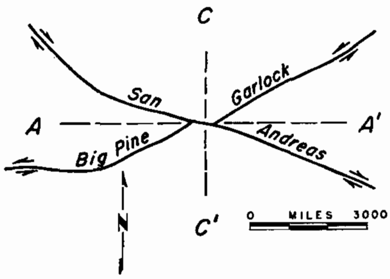

FIGURE 6.—SAN ANDREAS AND BIG PINE-GARLOCK STRAIN SYSTEM
AA′ axis of relative extension; CC′ axis of maximum shortening

The diagram (Fig. 6) of the northwest-trending San Andreas right lateral shear zone and the northeast-trending Garlock-Big Pine left lateral shear zone shows the CC_1 axis of shortening and AA_1 axis of relative extension. This strain pattern is geotectonically important because its size of approximately 600 x 200 miles makes it a respectable sample of the earth's crust. Even this area of systematic deformation may be, however, only a portion of a much larger unit or even of secondary or tertiary order in relation to the primary strain systems of the crust. The amount of deformation since the inception of this shear system is probably also geotectonically important, but no conclusive evidence is now known by which to date the first displacements or determine the total cumulative movement on either of the fault zones.

Supposing, however, as now seems tenable, that the right lateral displacement on the San Andreas amounts to several hundred miles and the left lateral displacement on the Garlock-Big Pine zone totals several tens of miles, some of the consequences should be as follows: (1) The San Andreas was initiated first and much movement occurred on it before the inception of the Garlock-Big Pine fault; (2) After the Garlock-Big Pine was established, it caused the big bend in the San Andreas and was offset by the San Andreas; and (3) The Garlock-Big Pine zone interrupted the continuity of displacement on the San Andreas and thereafter the north-south wedges actually moved toward each other.

If one side of the San Andreas has actually done most of the moving, indicated by the progressive offsets of Figures 2 and 3, there now appears to be a basis for determining which was the mobile block. Thus after the inception of the Garlock-Big Pine zone and assuming crustal shortening, the north-south wedges have been moving toward each other. Therefore it seems probable that the east side of the San Andreas north of the Garlock fault has actually been moving, as has the west side south of the Big Pine fault (Fig. 6).

Stress Pattern

The character and orientation of the forces responsible for the primary strain pattern of this large region are not readily definable. Even in this fortunate case where the fault characteristics and relationships clearly show a pattern of deformation, there are many orientations of deforming forces which could cause the observed deformation. An example in which the character and orientation of deforming forces are more obvious is in the case of "feather joints" (Cloos, 1932) where the fractures can be related to secondary forces which arise from known movements. In the case of the subject region, however, we are dealing with the major known deformation and thus cannot know the character and orientation of the causal forces. On the other hand, by knowing the deformational pattern of this region, it may be possible to resolve its relationship to a larger strain pattern which may in turn indicate the stress pattern in this region.

At present, however, only general deductions may be made. The first of these is that the deformation is probably the result of compressive stresses because: (1) experimental work shows that rocks are brittle enough so that tensional stresses would be apt to cause tensional fractures instead of this shear pattern, and (2) regionally important thrust and reverse faults and folds show prominent crustal shortening (and prominent upward relief with the AA_1 axis of extension locally oriented vertically). Thus, assuming compressive stresses, the possible effective orientations (Fig. 7) are north-south oppositional forces, or a northeast-southwest counterclockwise couple, or a north-west-southeast clockwise couple. The northeast-southwest counterclockwise couple is favored

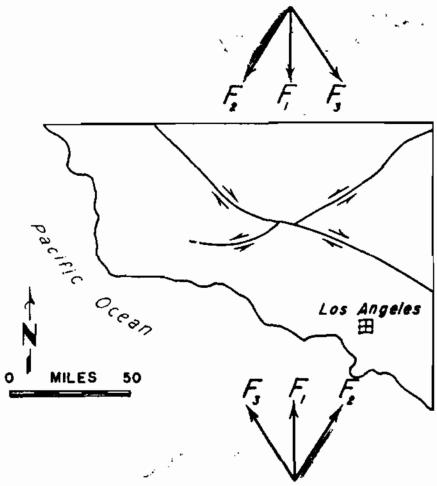

FIGURE 7.—STRESS SYSTEMS FOR SAN ANDREAS AND BIG PINE-GARLOCK FAULTS

F_1 direct compression; F_2 counterclockwise rotational compression; F_3 clockwise rotational compression.

because this orientation could perhaps more logically cause both the prominent northwest-trending folds of the Coast Ranges and the east-west folds and reverse faults of the Transverse Ranges (by upward relief in combination with the north-south shortening of the major shear pattern). With directly acting north-south compression, a more nearly equal manifestation of the shear sets would be expected, whereas the northwest right lateral set greatly predominates in this region. Likewise a north-west-southeast clockwise couple is unlikely because, where local upward relief occurred, the folds would be likely to trend northeast-southwest, whereas the general trend of folds in the Coast Ranges is northwestward.

GENETIC CONCEPTS AND CONCLUSIONS

Because the San Andreas and Garlock-Big Pine fault zones are major structures of great length, depth, displacement, and age; because they constitute a strain pattern of north-south shortening; because the probable orientation of causal forces is northeast-southwest; and because these forces are operative at great depth, a drag mechanism due to flowage of rock material from the Pacific basin to the continent of North America may be the primary reason for deformation in this region.

The mechanical effect of subcrustal convection currents, a presently favored concept (Gilluly *et al.*, 1951), may have caused this deformation. Such a drag effect near oceanic margins could, then, be responsible for the permanence and growth of continents, development of geosynclines, deformation of geosynclinal deposits, association of metamorphic and igneous rock facies with orogeny, development of mountain roots, and possibly, the development of major lateral fault systems.

If the major lateral fault system described here is really so directly related to primary forces of deformation, much advancement in the understanding of geotectonics may be expected by the world-wide study of such faults. Perhaps faults with lateral displacements of hundreds of miles could even be responsible for some geologic relationships which seem to require land bridges.

Entirely apart from these speculations, the following conclusions are attained. First, the mapping of the faults and the evidence for the sense of the displacements are considered reliable. Second, the essential contemporaneity of the faults is considered to be proved. Third, this pattern of conjugate shears with opposing centripetal and centrifugal moving wedges is believed to be mechanically sound. Fourth, this strain system shows definite north-south shortening and relative east-west elongation of, during its activity, at least tens of miles and affecting a crustal area of at least 120,000 square miles; as such it is of significant proportions with respect to earth deformation. Fifth, this strain system is, as far as known, compatible with lesser structural features in the region and has in itself set up stress conditions which have developed lower-order strain systems. This major tectonic pattern in California may thus provide a satisfactory framework for the understanding of many elements of deformation within this region. Sixth, if deformation in other large areas proves to be compatible, it may ultimately be possible to develop a system of primary geotectonic forces. Hopefully this approach could, in conjunction with other lines of research, culminate in a usable theory of the causes of earth deformation.

Before the geologic history of California is satisfactorily established, much more critical mapping is needed, especially to determine the sense, duration, and amount of lateral movements on faults. Displacements which are measured in miles will have significant effects on paleogeologic and paleogeographic maps, and even those which are measured only in thousands of feet may, for example, be very critical in studies of the distribution of sedimentary facies. As these data accumulate, we can expect to attain a more nearly complete story of the dynamic geologic history of the region.

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