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The California Coast Ranges

JOHN C. CROWELL*

ABSTRACT

Western California between the 37th and 40th parallels is part of an active mobile orogenic belt in which sedimentation, deformation, volcanism, and plutonism have been intimately associated since the mid-Mesozoic. At present, the region is still undergoing folding and warping as shown by data from geodetic triangulation networks and geomorphology, and several major high-angle fault zones are seismically active. These faults continue to acquire displacement both suddenly during earthquakes and slowly by gentle creep with no recordable shocks. Pleistocene beds and terraces at places are steeply warped. Strong deformation occurred during the late Pliocene and early Pleistocene. Most of the Tertiary was characterized by fragmentation of the region into basins and intervening ranges following comparatively more widespread sedimentary transgressions and regressions during the early Tertiary and late Mesozoic.

The structural significance and history of the San Andreas fault system are still under study. In central California, Pliocene and Pleistocene sedimentary facies are apparently offset laterally as much as 25 miles, but in this region strike-slip of greater amounts in older rocks has not yet been documented. The San Andreas separates very different terranes, with mismatched stratigraphic sections facing across the fault. These probably can be matched only through recourse to major right-slip, increasing in displacement with age. Right-slip of about 200 miles is reasonably well established in southern California, and such displacements, extended into central and northern California, probably account for the contrast in terranes, including basement. Here the San Andreas separates the Franciscan complex of disturbed graywacke, mudstone, chert, conglomerate, limestone, mafic and ultramafic volcanic rocks and serpentine, and associated metamorphic rocks from the basement of granites and gneiss. The magnitude and timing of displacements on the San Andreas and related faults, which probably originated in the early Tertiary, will only be determined through the mapping and correlating of sedimentary facies that are cut and offset by the fault. As yet this analysis has but barely commenced.

The Sierra Nevada and Klamath Mountains were the site of rapid eugeosynclinal sedimentation and volcanism in early Late Jurassic time. These strata were deformed, metamorphosed, faulted, and intruded by serpentine and granitic plutons in turn; all in the mid-Late Jurassic. Following uplift, deep erosion, and subsidence, sedimentation in the latest Jurassic transgressed and overlapped eastward across the ancient Sierran margin. Altogether, 40,000 feet of mudstone, graywacke, and conglomerate were deposited in the Great Valley sequence by the end of the Cretaceous. Beginning also in the early Late Jurassic nearby, but in unclear tectonic relationship to the Great Valley sequence, Franciscan sedimentation, volcanism, and downbuckling carried strata to depths of about 70,000 feet. Here deeper beds were converted to the blueschist metamorphic facies and then rapidly elevated and perhaps in part thrusted in mid-Late Jurassic time. Following continued eugeosynclinal sedimentation, major thrusting or downslope sliding and mixing on a grand scale took place in the Franciscan terrane in the Middle Cretaceous. The complexity of the Franciscan is the consequence of these events together with overprints of Tertiary deformation, which at places also included major thrusting and near isoclinal folding, diapir or piercement structures, limited gravitational sliding, and strong deformation along high-angle shear zones.

Ancient and complex rocks of the thick continental crust give way abruptly to the simple, thin, and presumably younger crust beneath the Pacific Ocean. The Moho discontinuity has a depth of about 18 miles (29 km) under the Coast Ranges and rises to about 8 miles (13 km) under the basaltic oceanic crust. Pacific fault zones apparently pass largely beneath, and only slightly disturb, the continental plate. Faults of the San Andreas system probably are mainly confined to the continental plate and may converge and merge to constitute the continental margin.

INTRODUCTION

The tectonics of the California Coast Ranges and Great Valley between the 37th and 40th parallels are marked by complexity and controversy. The region is part of a mobile tectonic belt that has undergone intricate deformation through long geologic periods which at times have culminated in metamorphism and plutonism. Concurrently with intermittent deformation, sedimentation and volcanism, both marine and nonmarine, have taken place. The complexity is the direct result of this long continued interplay between deformation, sedimentation, volcanism, metamorphism, and plutonism. Older rocks and tectonic units have been deformed time and time again, and in

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many instances, successively in quite different ways. Late strong tectonic events have overprinted and largely obscured the evidence for early events. Folding and faulting of many types have affected these rocks, both young and old, and roadcuts and large-scale maps of small areas document clearly this widespread deformation. During the past few decades, however, as more information from mapping and from stratigraphy and the patterns of sedimentation has become available, geologists have been forced to consider seriously explanations involving major thrusting, major strike-slip faulting, major down-slope sliding, and piercement or diapir tectonics in order to account for the present distribution of rock units. Data from the study of mineral facies in blueschist and associated rocks indicate that terranes have been quickly and deeply buried within the crust, to depths exceeding 70,000 feet, and then have been very rapidly uplifted. Evidence and arguments, accordingly, strongly suggest that there are vertical movements exceeding 5 miles, sideways movements of blocks on major wrench faults exceeding 200 miles, giant overthrusts with horizontal displacements of as much as 100 miles, and vast tracts of jumbled blocks as the result of downslope sliding of many tens of miles. No wonder that the region is complex, and no wonder that there is brisk controversy among the geologists who puzzle over its tectonic history.

Although the main purpose of this article is to present a tectonic cross section through the Coast Ranges (Fig. 1), this cannot be done satisfactorily without taking into consideration the geologic history of the terrane involved. It is not enough to present a picture of the geometry of the rock units as they now lie. In fact, geologists in time will be able to draw a meaningful cross section only if they work out carefully the way the rock units got into their present positions. We cannot extrapolate faults, folds, and units downward only on the information obtained at the surface, from wells, and from geophysical data. We can do a much more satisfactory job if we have a genetic image in mind. But as yet, we do not quite have enough basic data from mapping and other studies to frame images satisfactorily. Alternative hypotheses and explanations for the relations as now known are being sifted and checked. We are on the edge of understanding in placing the various tectonic processes in their proper order and perspective, and real understanding can be expected in the next decade or so. At best, a discussion now is but a progress report and a treatment of current ideas and explanations.

One appealing way to describe the tectonic history of the Coast Ranges is to work back from the known present into the more obscure past. The interplay between deformation and sedimentation is clearly documented in the Recent and late Cenozoic rocks. Perhaps we can develop working guides in strata which have not yet been seriously deformed to help us in interpreting the record in more ancient rocks, in those where later events have largely obliterated the data needed for interpretation. So in this paper, I will describe very briefly the present-day topography and the changes which we can observe and measure taking place upon it, and work from these back into the past. I will lean upon the Principle of Uniformitarianism and extrapolate from the present where the data are good and into the past where the data are progressively less satisfactory. Basic to this approach is the realization that young rocks can only record deformations which are also young and which have happened after deposition. The large expanses in the Coast Ranges with older rocks exposed at the surface, such as the Franciscan complex, show the stamp of many deformations; these are indeed very difficult to disentangle. Such terranes have been subjected to the later events as well as the older, and one way to appraise the effect of the younger ones is to remove or unravel them graphically, or in our imagination, from the others. To do this we may need to project with care results from one region into another, for example, from a region where younger strata are exposed into an adjacent one where older rocks crop out.

MODERN AND RECENT DEFORMATION

The region under treatment, between the Sierra Nevada and the deep Pacific Ocean, can be subdivided into several topographic provinces today, although the area must have appeared very different in the past (Fig. 2). The Sierra Nevada with its foothills borders the region on the east as well as the Sacramento Valley, the northern half of the Great Valley of California. Here the valley is about 40 miles wide and lies very near sea level. Broad and gentle alluvial fans, dissected at their heads, reach downward and westward from the Sierra foothills to the meandering and swampy Sacramento River. The delta region, where the Sacramento joins the San Joaquin River and where they both lazily flow westward to San Francisco Bay, is clearly one of modern tectonic subsidence and sedimentation. Next to

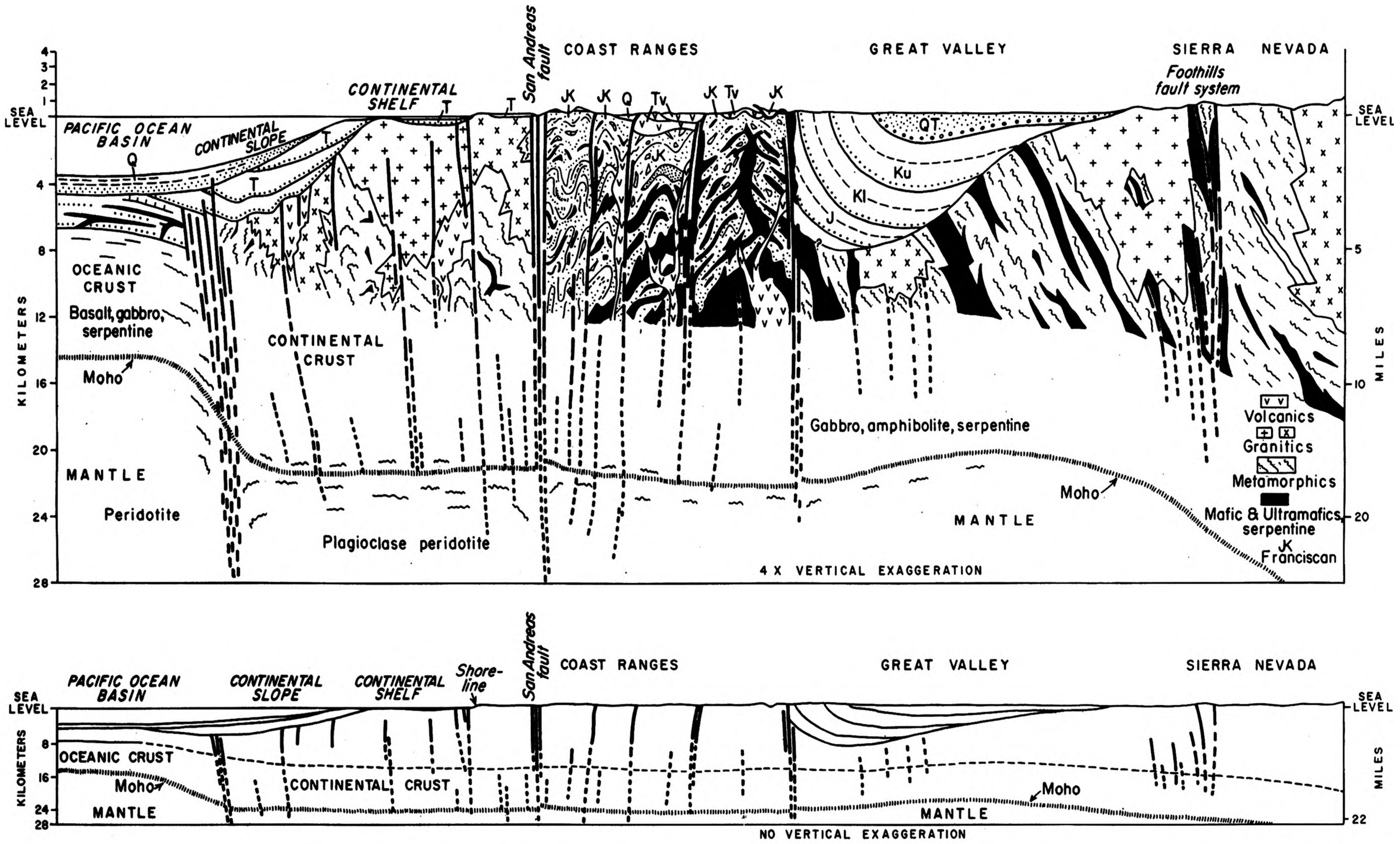

Fig. 1. Schematic tectonic cross section from Pacific Ocean Basin to Sierra Nevada foothills. Section crosses a few miles north of Point Reyes (PR, Fig. 2) through Sacramento (SA). Data in part from Thompson and Talwani (1964); Bailey and others (1964); Hamilton and Pakiser (1965); Jennings and Burnett (1961); Koenig (1963); Strand and Koenig (1965). Vertical exaggeration 4X on upper section; no exaggeration below. J = Jurassic; K = Cretaceous; Kl = Lower Cretaceous; Ku = Upper Cretaceous; T = Tertiary; Tv = Tertiary volcanics; Q = Quaternary.

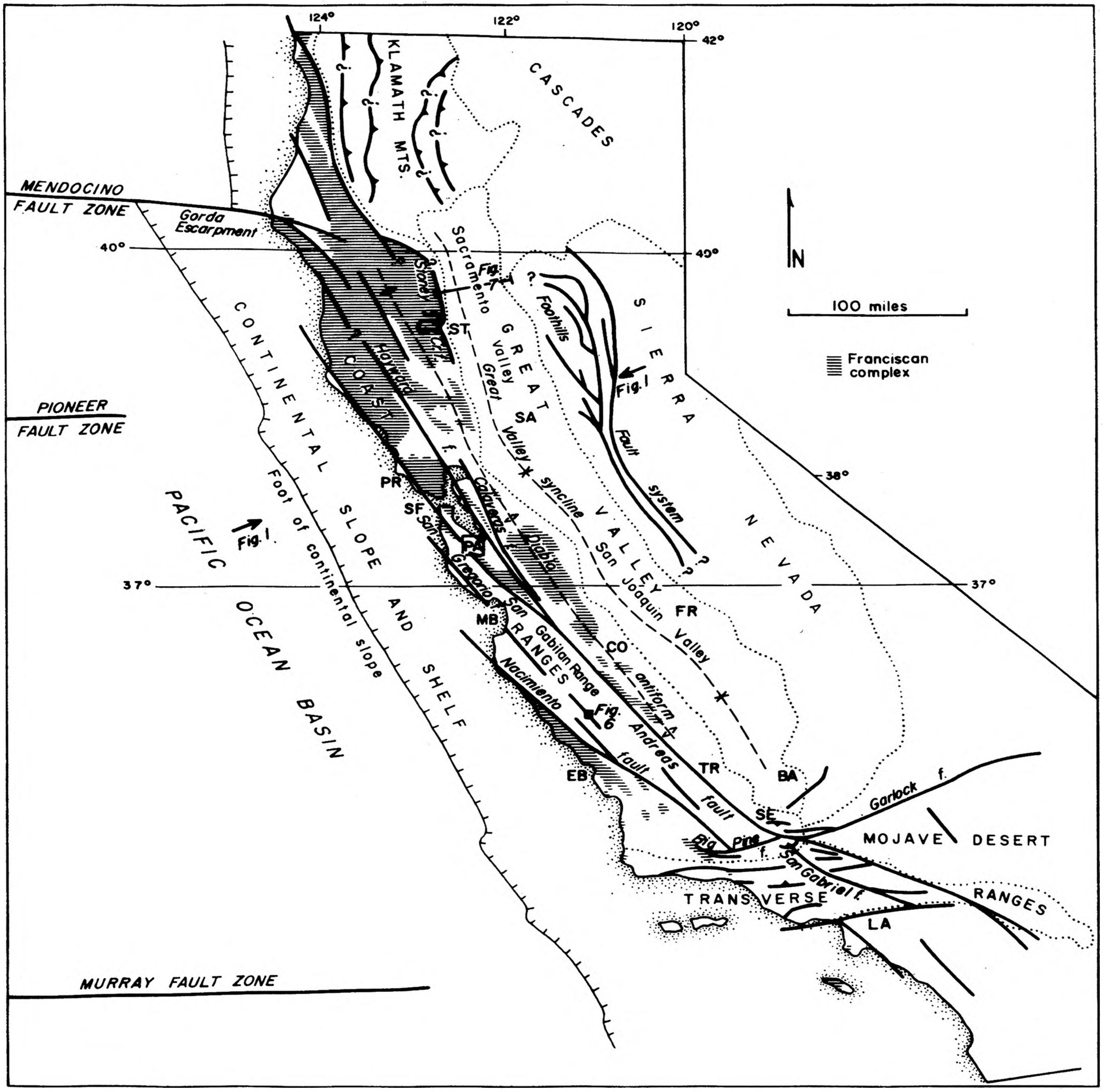

Fig. 2. Sketch map of California showing major geologic features and provinces. Data in part from Bailey and others (1964); Clark (1960); Dott (1965); Irwin (1964). BA = Bakersfield; CO = Coalinga; EB = Estero Bay; FR = Fresno; LA = Los Angeles; MB = Monterey Bay; PA = Palo Alto quadrangle; PR = Point Reyes; SA = Sacramento; SE = San Emigdio Mountains; SF = San Francisco; ST = Stonyford; TR = Temblor Range.

the west lie the Coast Ranges themselves, consisting of a series of northwesterly striking and subparallel mountain ranges with intervening valleys. Many of the valleys are now receiving sediments as the mountains are eroded, but most of the erosional products work their way down longitudinal rivers to the sea. Some of the ranges still retain patches of Pleistocene and early Recent alluvial terraces which attest to the recency of uplift. The western part of the region is made up of the continental shelf, from 20 to 30 miles wide, and the continental margin, about 40 miles wide. From a depth of 600 feet at the edge of the continental shelf, the water drops away across the continental margin to a depth of more than 12,000 feet in the deep Pacific. In summary, the Sacramento Valley at present is an elongate region of subsidence and sedimentation, the area of the Coast Ranges is largely a region of uplift and erosion but with local areas of sedimentation, and the continental shelf and margin are mostly areas of nondeposition or minor deposition and some erosion. Most of the sediment from the region works its way to the floor of the Pacific, in part down submarine canyons, and into vast submarine aprons which attenuate westward from the base of the continental slope.

Deformation at present is shown dramatically in ways other than by inferences from the geomorphology. Coastal California is seismically active, and at times of strong earthquakes the ground is broken and displaced at the surface along faults. Streams, fences, and roads, for example, were moved laterally as much as 21 feet during the San Francisco earthquake of April 18, 1906, on the San Andreas fault. In addition to such sudden movements, manmade structures along the San Andreas and Hayward faults are being bent and offset by tectonic creep, even without the occurrence of recordable earthquakes (Steinbrugge and others, 1960; Cluff and others, 1966). Resurveys of triangulation networks in the central Coast Ranges show that the terrane is moving laterally, both by folding and warping within blocks between faults, and by creep or slippage on the faults themselves (Whitten, 1956). Analysis by Burford (1965) of data

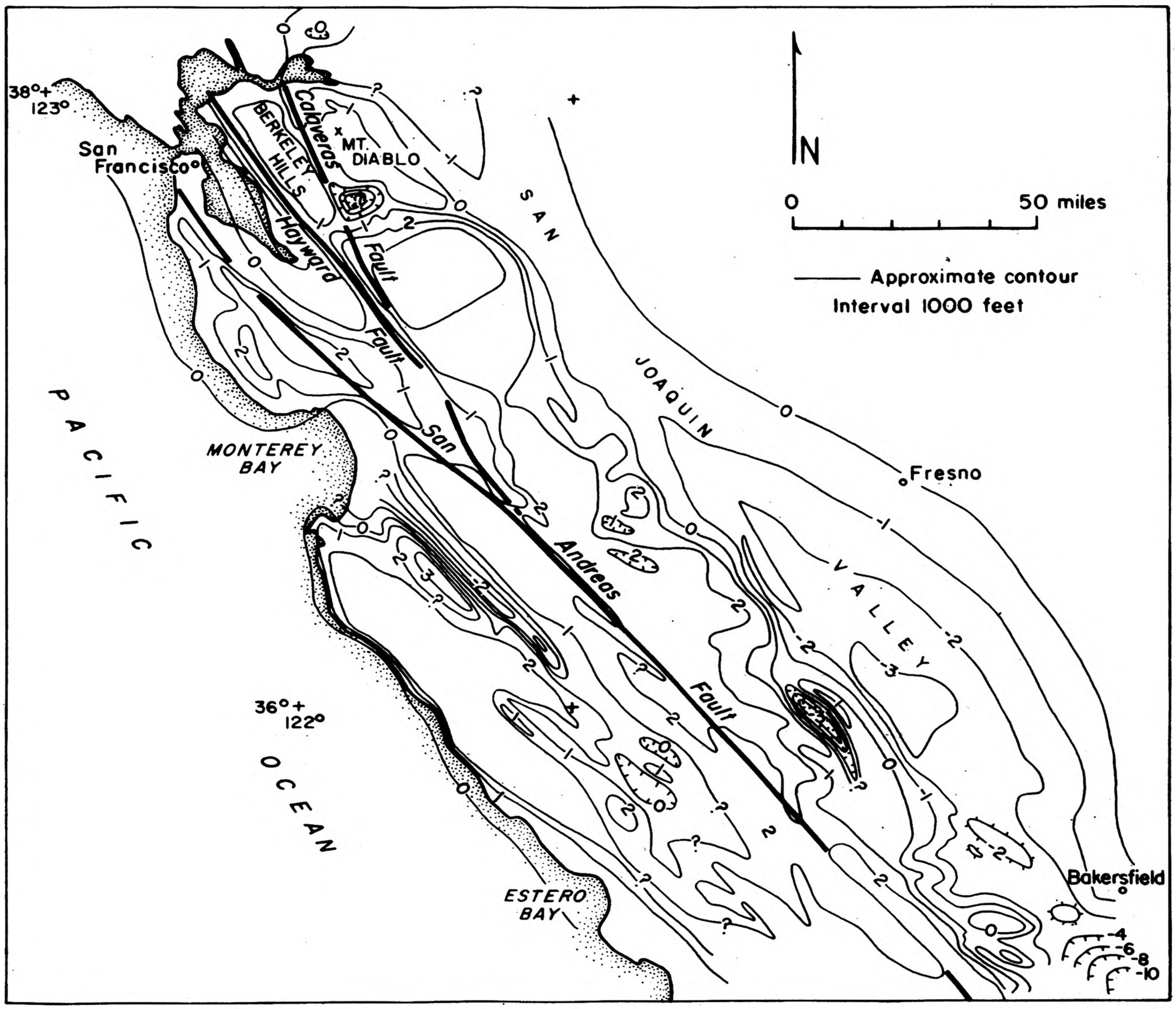

Fig. 3. Contour map of the approximate present configuration of a surface that was the geoid approximately 3 million years ago. Simplified from Christensen (1965, Pl. 2); *q. v.* for qualifications, sources of data, and discussion.

from surveys for two networks which cross the Coast Ranges and the San Andreas fault, one northeast from Monterey Bay and the other from Estero Bay, show a dominant northeast-southwest crustal shortening which is approximately perpendicular to the general trend of folds, reverse faults, and thrusts in the Coast Ranges. In the vicinity of the San Andreas fault zone, however, the strain pattern is characterized by north-south contraction and east-west extension which is consistent with right-slip on steep faults with a northwest strike. On a regional basis, these studies show that deformation associated with northeast-southwest crustal shortening dominates the movement pattern at present and that somewhat subordinate right-lateral displacement is superimposed on this general pattern and is restricted to the San Andreas fault zone.

PLIO-PLEISTOCENE DEFORMATION

The vertical deformation over a somewhat longer interval is shown by the present shape of a hypothetical geoidal surface that existed about 3 million years ago (Christensen, 1965). The study of localities around the margins of valleys, where late Cenozoic strata are preserved and their ages known, of ancient erosion surfaces, and, where this kind of information is lacking, of topography, with a consideration of erosion rates, permits the construction of a contour map (Fig. 3). Despite gaps in the record and inaccuracies in the method, the study reveals that various ranges and valleys within the Coast Ranges have moved vertically as much as 3,000 feet during this time interval. The map brings out that the major strike-slip faults, such as the San Andreas, in this region are somewhat independent of vertical uplifts although they are aligned with the same trend; a relation which is also shown by the course of these faults across the present topography. Only locally do these faults today form the boundary between high-standing terrane under erosion on one side and low-standing ground receiving sediments on the other. The map also emphasizes that sedimentation is rapid in the southern part of the Great Valley, in the area now characterized by internal drainage. Over 3,000 feet of [illegible] have been laid down in the San Joaquin Valley near the 38th parallel and perhaps as much as 10,000 feet to the southwest of Bakersfield. Our efforts to understand the tectonics of the region must therefore be concerned, not only with the rise of mountains, but also with the formation of these amazingly deep "holes" well back within the continent from the Pacific margin.

The horizontal deformation in the Coast Ranges during the latest Cenozoic is shown by the offset of streams and terrace facies along the San Andreas and related faults. Unfortunately, in the study of lateral movements in crustal rocks, we lack conveniently oriented references from which to measure the movements, such as the omnipresent sea-level surface which controls erosion and sedimentation and which we can use for judging vertical movements. Only in the immediate vicinity of faults, such as the San Andreas, is there any possibility of determining the relative horizontal movement, and then only if we can find offset, near-vertical, planar contacts, such as those between plutons, or displaced linear elements, such as offset streams or facies-change lines. The data we have to work with in documenting lateral movements is more scarce than that which we can use in documenting vertical movements. Moreover, studies using contoured surfaces such as those just described that were undertaken by Christensen (1965) to deal with vertical changes are largely insensitive by their geometric nature to horizontal movements. Nevertheless, we have definite evidence of nearly pure strike slip for the San Andreas, as shown by the offset of roads, fences, and streams during the 1906 earthquake and by older displacements. Geometrically, these are linear features which intersect the fault at high angles and which can be correlated from one side to the other after offset. Stream offsets of as much as 3,000 feet have been reported along the San Andreas (Noble, 1954, p. 46), and many in between, but to date there have been no careful geomorphic studies showing the increase of displacement with age. At several places, displacement of as much as 10 miles of facies-change lines in Pleistocene terrace gravels has been reported (Wallace, 1949, p. 800; Hill and Dibblee, 953, p. 446; Noble, 1954, p. 46; Smith, 1959). In summary, lateral movements on active wrench faults of the Coast Ranges have taken place at the same time as striking, and more easily documented, vertical movements.

Pliocene rocks, mainly upper but also ranging down into the middle Pliocene and up into the lower Pleistocene, along the San Andreas fault, have been studied by Higgins (1961) in order to learn more about the displacement of the fault. Embayments filled with these marine strata east of the fault must have had channelways facing into the Pacific across the

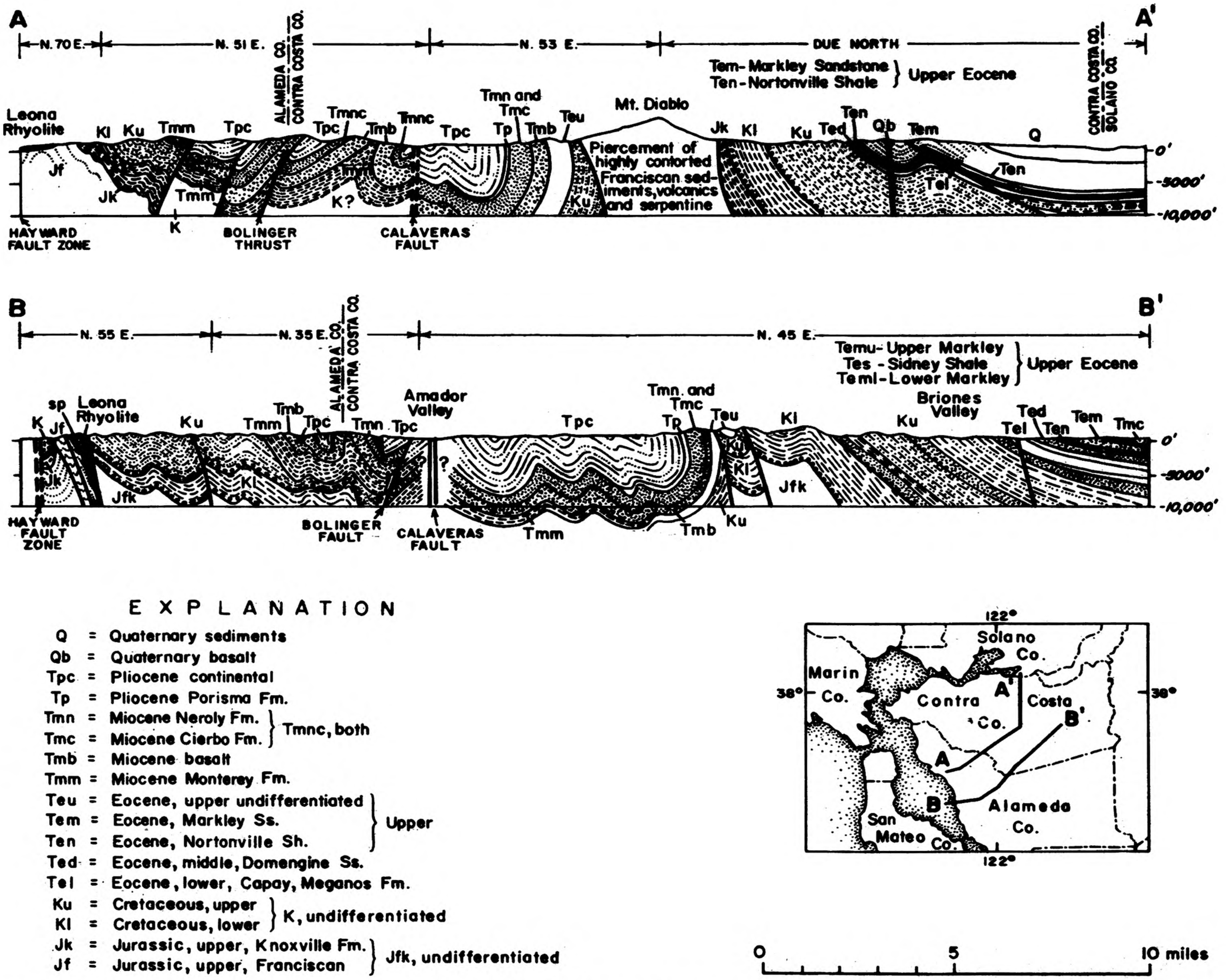

Fig. 4. Geologic structure sections through the Mount Diablo region. Redrawn from Taliaferro (1951, Pl. 1, Sections Va-Va' and VI).

fault when they were laid down, but now the openings are blocked by ridges of older rocks. By matching possible seaways now offset to the north, Higgins concluded that right-slip " . . . has not exceeded 15 miles, more likely has amounted to 4 to 10 miles, and possibly has not exceeded 1 to 1½ miles since middle Pliocene time. During the same time, vertical movements have raised the east side of the fault about 500 feet relative to the west side in some areas."

TERTIARY DEFORMATION

The tectonic record for the middle Pliocene and earlier times in the Tertiary comes primarily from interpretations of the stratigraphic record, both sedimentary and volcanic. Although geomorphic features which had their origin early in the Pliocene, and even before, are still preserved locally, they are so scattered and piecemeal that they are not especially helpful in reconstructing the geologic history of the region. Lower and middle Pliocene sediments, marine and nonmarine, are widely preserved in the central Coast Ranges and have a distribution which is only partly controlled by the present topography. These beds are markedly deformed, and at many places they stand vertically and are even overturned (Fig. 4). In fact, because upper Pliocene and younger beds are much less deformed than middle and lower Pliocene strata in the San Francisco Bay region, Taliaferro (1951, p. 142) writes of a strong mid-Pliocene deformation which he considered as the most important diastrophic event in the development of the Coast Ranges as we know them today. These events actually began in the late Miocene with the development of a series of basins and highs which fragmented the topography in the central Coast Ranges. One of these ridges or high-standing areas, which contributed debris to nearby lowlands, extended from south of San Francisco in a southeasterly direction (Taliaferro, 1951, p. 144). To the southwest of this high, a thick section of marine clastic and organic sediments was laid down; these beds (the Purisima Formation) are preserved locally from the coastline west of the San Andreas to the San Joaquin Valley region near Coalinga. As yet, however, there has been no detailed regional study of the facies, thickness, and sedimentation directions in these strata which might provide data to assess the magnitude of post-mid-Pliocene strike slip on the San Andreas and related faults. Northeast of the high-standing region referred to above are thick sequences of variable continental deposits, some of which were derived from the southwest (Taliaferro, 1951, p. 144). These beds are intercalated with thick flows and agglomerates of both rhyolite and andesite. On to the northeast and east, these units give way to thinner nonmarine beds in the Great Valley, and these in turn interfinger to the south with marine Pliocene beds in the vicinity of Fresno.

Miocene strata, both sedimentary and volcanic, of the central Coast Ranges are characterized by marked facies and thickness changes from place to place. At the beginning of the Miocene, the sea encroached upon an uneven land. South of the Monterey region, for example, lower Miocene sediments (Vaqueros Formation) were laid down between the islands of a complex archipelago (Taliaferro, 1951, p. 139). As time passed, however, relief of the land area was reduced, and thick middle Miocene strata, including organic shales largely composed of diatoms (Monterey Formation), were laid down in basins. Volcanism was widespread, and from several marked centers produced both subaerial and submarine flows, fragmental rocks, and shallow intrusions. The range of composition of these rocks is striking; rhyolite, andesite basalt, and analcite diabase are represented. Toward the end of the Miocene, sandstone and, locally, conglomerate replace the widespread and thick organic shales. From the tectonic viewpoint, the mid-Tertiary in this region was a time of crustal instability when basins were downwarped and intervening highland areas were upfolded. Locally there are sharp intra-Miocene unconformities, especially around the margins of some basins. It has been extremely difficult to work out the deformational history of the mid-Tertiary, primarily because of the complexity of the stratigraphy. Only by means of careful large-scale mapping, quadrangle by quadrangle on a regional basis, can the story be satisfactorily documented. This work is still incomplete. The work depends primarily on sound stratigraphic procedures so that time correlation from place to place can be established independently from the lithology. Careful mapping of facies changes, with particular attention to directions of sedimentation and thickness changes, source areas of conglomerates, and environmental indicators preserved in the rocks, will allow geologists of the future to reconstruct the changes in Miocene paleogeography. Such detailed regional studies as well will permit the search for mismatches in stratigraphic sequences across fault zones that perhaps can only be resolved by appeal to major strike slip.

The tectonic history and significance of the San Andreas fault system between the 37th and 40th parallels of latitude are difficult to decipher, and much of our understanding of the fault will have to depend on conclusions obtained from elsewhere along it and then cautiously applied to this region. The problems can perhaps be framed best by referring to the contrast in formations exposed on the two sides of the fault in a typical area, such as that in the southern part of the San Francisco Bay area, described recently by Dibblee (1966) and reproduced here as Figure 5. To begin with, the sequence on the southwestern side of the fault extends downward, outside of the quadrangle, to include Paleocene strata lying unconformably on the granitic and metamorphic basement underneath the Butano Sandstone (Eocene). In fact, everywhere along the southwestern side of the San Andreas zone, sedimentary strata, not at all metamorphosed, lie depositionally on deeply eroded rocks containing granitic intrusions which have been dated isotopically as being between 81 and 92 million years of age, or early Late Cretaceous (Curtis and others, 1958). On the northeastern side of the fault (Fig. 5), the Butano (?) Sandstone lies unconformably upon the Franciscan complex which consists of a thick heterogeneous sequence of graywacke, greenstone, chert, limestone, shale, and associated serpentine and diabase. This complex in California is now

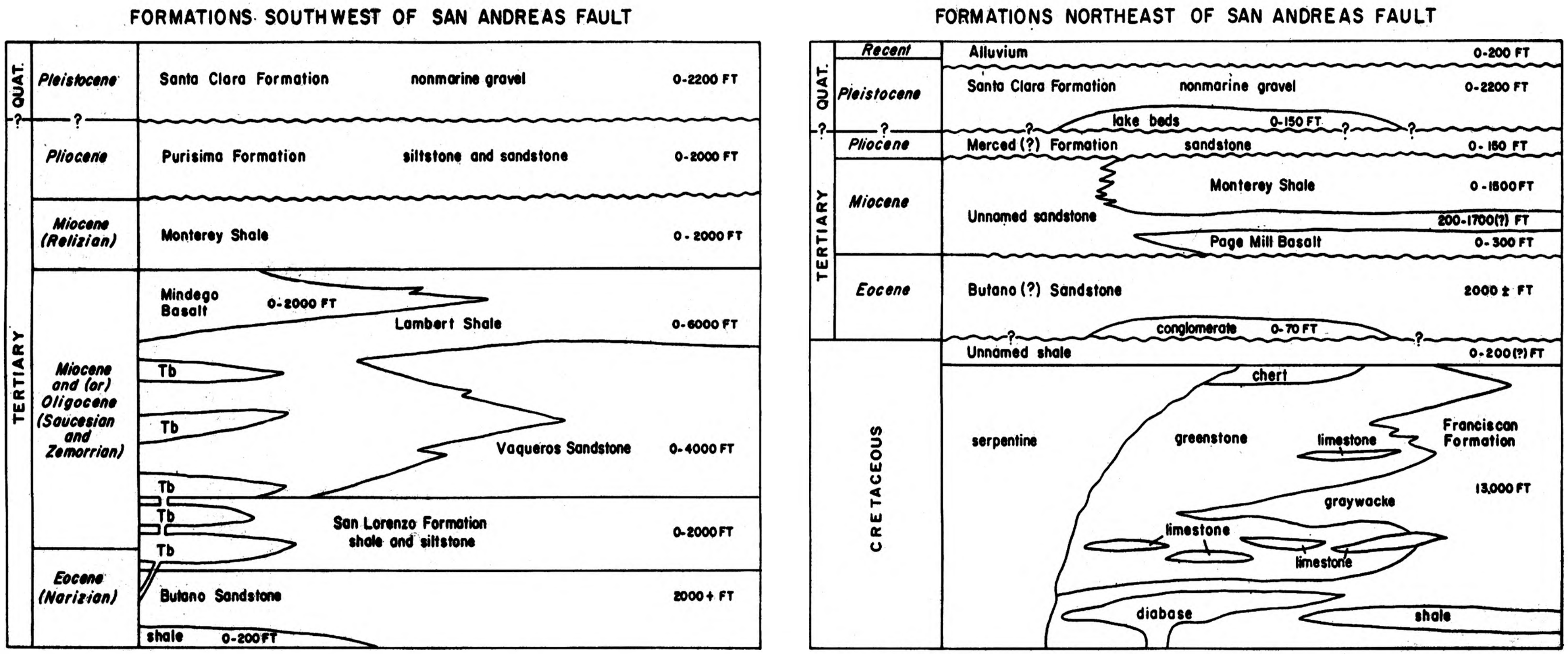

Fig. 5. Diagrammatic stratigraphic sections of Palo Alto quadrangle. Redrawn from Dibblee (1966). See Figure 2 for location, and text for discussion.

known to range in age from Late Jurassic to Late Cretaceous (Bailey and others, 1964). On one side is a sialic basement made up largely of Late Cretaceous granite; on the other is a terrane of mainly older sediments which are predominantely unmetamorphosed, although they locally contain rocks of the zeolite, blue-schist, and eclogite metamorphic facies. So the first and perhaps most basic problem we face in understanding the significance of the San Andreas in our region is to explain this contrast in the underlying or pre-Tertiary rocks, but we will come back to a discussion of Mesozoic and older events later.

The contrast in Tertiary units is brought out by Figure 5. The Butano Sandstone, defined on the southwest, consists of bedded, hard, arkosic sandstone with intercalations of siltstone. On the northeast, it is similar but more massive in lithology and contains a basal conglomerate where it lies unconformably on the Franciscan complex. On the southwest, the Butano is overlain conformably by the San Lorenzo Formation, but the later unit is not present at all in this region on the northeast. Instead, here the Butano (?) is overlain unconformably by the Page Mill Basalt, a Miocene unnamed sandstone, and the Monterey Shale. On the southwest, the San Lorenzo Formation is overlain conformably by the Vaqueros Sandstone and Lambert Shale, units which are not present at all on the northeast. The Lambert Shale, with included basalt tongues (Mindego and others), is overlain conformably by the Monterey Shale. In striving to explain such a contrast in sequence, California geologists have traditionally first of all appealed to several movements on the San Andreas during the Tertiary, with dip slip primarily. According to this thinking, during the Paleocene and Eocene the northeastern block would have stood somewhat higher than the southwestern which received Paleocene and Butano sandstone and shale. The sandstone, with a local basal conglomerate, transgressed across the bevelled Franciscan complex to the northeast and then was presumably uplifted and somewhat eroded, as shown by the unconformity above. This northeastern block was then depressed sufficiently to receive the Miocene unnamed sandstone, Page Mill Basalt, and Monterey Shale. In the meantime, the southwestern block received a thick and variable, conformable sequence on top of the Butano Sandstone that included the San Lorenzo Formation, Vaqueros Sandstone, Lambert Shale, and Mindego Basalt before the Monterey Shale was laid down conformably over all. The mismatch of stratigraphic sequence across the fault would probably be explained by correlating the unnamed sandstone with a tongue of the Vaqueros Sandstone and assuming that the Lambert Shale was deposited only on the low and subsiding block on the southwest. The Page Mill Basalt would then probably be correlated with some of the southwestern basalts (Tb or Mindego). According to this interpretation, the unconformity beneath the Miocene rocks on the northeast is represented on the southwest by the continuous sequence of San Lorenzo Formation and parts of the Vaqueros Sandstone and Lambert Shale. Following these events, blocks on both sides of the San Andreas were sufficiently uplifted to form the unconformity on top of the Monterey Shale. The block on the northeast remained high, however, while that on the southeast received the Purisima Formation during the early and middle Pliocene. It was then somewhat elevated while the northeastern block was depressed to receive the upper Pliocene, Merced (?) Formation. Both blocks were then elevated sufficiently to make the sub-Santa Clara unconformity; then there was enough subsidence to deposit the Santa Clara Formation, consisting of nonmarine gravels.

Until the early 1950's, few geologists challenged such a complicated interpretation of the differences in the stratigraphic sequences across the San Andreas, as well as across other major faults in California. It seemed well established that the major faults separated blocks which alternately rose and sank as the consequence of fundamental "vertical tectonics". Although the idea of explaining such differences by appeal to strike slip of several tens of miles had been advocated, on the Calaveras-Sunol fault by Vickery (1925), on the San Andreas in southern California by Noble (1926), and on the San Gabriel fault in the Transverse Ranges by Crowell (1952), the idea did not receive much attention until the publication of Hill's and Dibblee's paper in 1953. Their contribution primarily was to show that several of the stratigraphic sequences on one side of the San Andreas were apparently reproduced on the other, but offset an astounding number of miles. Successively older sequences, beginning with contrasts in Pleistocene terrace facies, appeared to be offset more and more in going back in geologic time. They suggested that many of the marked contrasts across the fault were but dip separations and that the fault had moved primarily by strike slip—an extrapolation backwards into time of the type of movement demonstrated today by seismic and surveying studies. In short, they resolved the "mismatch" in stratigraphic sequences across the fault, for selected units, by showing that certain sequences were sharply truncated at the fault and could be "matched" on the other side but displaced many miles laterally.

The region including the southwestern corner of the Palo Alto quadrangle was one mentioned by Hill and Dibblee (1953, p. 449 and Fig. 3). They were impressed with the similarities of the Eocene sequence, including the Butano Sandstone, of the Santa Cruz Mountains with strata of the same age, containing similar faunas, in the San Emigdio Mountains south of Bakersfield and suggested a post-Eocene displacement of about 225 miles. Somewhat younger units, including the San Lorenzo Formation as represented in the northern part of the Gabilan Range (also southwest of the San Andreas), appeared to match strata in the San Emigdio Range on the other side. In each of these distant areas, an unusual section of lower Miocene volcanics, red beds, and marine lower Miocene and Oligocene strata occurs. They therefore suggested a post-early Miocene right slip of about 175 miles. As yet, however, no detailed comparison of either the Eocene or Oligocene-lower Miocene strata has appeared in the literature, and many geologists are unwilling to accept such long distant correlations. These geologists are impressed, for example, with the fact that Eocene sandstone (Butano) is preserved on both sides of the fault, and that although there are differences in facies, thickness, and especially in relations to younger and older rocks, these differences are not unusual in California. They state that if you go a specific distance laterally along the San Andreas, but stay on one side of it, the facies and thickness changes will be about the same order as those observed in crossing the fault.

We therefore face two very different hypotheses which need testing, and it is obvious that the data for such tests must come from detailed stratigraphic studies. Within the Palo Alto quadrangle, for example, we need to search for evidence within certain of the stratigraphic units that the San Andreas fault was active during deposition and that these beds were not truncated sharply by faulting after deposition. Does the Butano Sandstone on the southwest (Fig. 5) contain Franciscan debris similar to the rocks of that complex exposed unconformably beneath the Butano (?) on the northeast? Is there any sharp change of facies in the San Lorenzo, Vaqueros, or Lambert in approaching the fault which might be credited to uplift and erosion of the northeastern block during time represented by the post-Butano (?) unconformity? Are there any distinctive pebble suites which could only have been derived locally from below one of the unconformities on a high-standing block and swept across the San Andreas to be deposited on the low block? These and similar questions need framing and answering.

To test the strike-slip hypothesis, we first need to establish that there is a sharp mismatch of stratigraphic units at the San Andreas fault. Units in the class which occur on both sides, such as the Butano Sandstone, Monterey Shale, and Santa Clara Formation (see below), need examination especially in order to see whether there is a contrast in facies, thickness, and other features across the fault. Others in the group, which are found on one side only, such as San Lorenzo, Vaqueros, and Lambert, need to be followed carefully to as close to the fault as possible to determine whether they are sharply truncated. These studies may establish that there is a puzzling "mismatch" with regard to these two classes of units. The strike-slip hypothesis is only proven, however, if these "mismatches" can be resolved by finding the offset counterparts displaced laterally. The difficulties with such essential studies are primarily twofold. In the first place, it requires more than the usual amount of attention to stratigraphic details in the particular area that a geologist is working. It is usually not enough to trace the major contacts between formations and to keep track of gross thickness and facies changes such as might be done in conventional mile-to-the-inch mapping. Time consuming, second order studies, such as pebble counts, directional-current, and other types of investigations, may be needed. In the second place, it may well be necessary to map and to examine critically terrane that is many miles from the quadrangle of primary interest. In fact, under the hypothesis that older rocks are displaced successively more and more, the search for a match will have to go farther and farther away as the rocks get older. And to be certain of correlations, we need to be knowledgeable concerning all of the rock in between to be sure that we haven't overlooked a patch of terrane where strata of the right age are exposed. In order to be truly sound, the task is an imposing one.

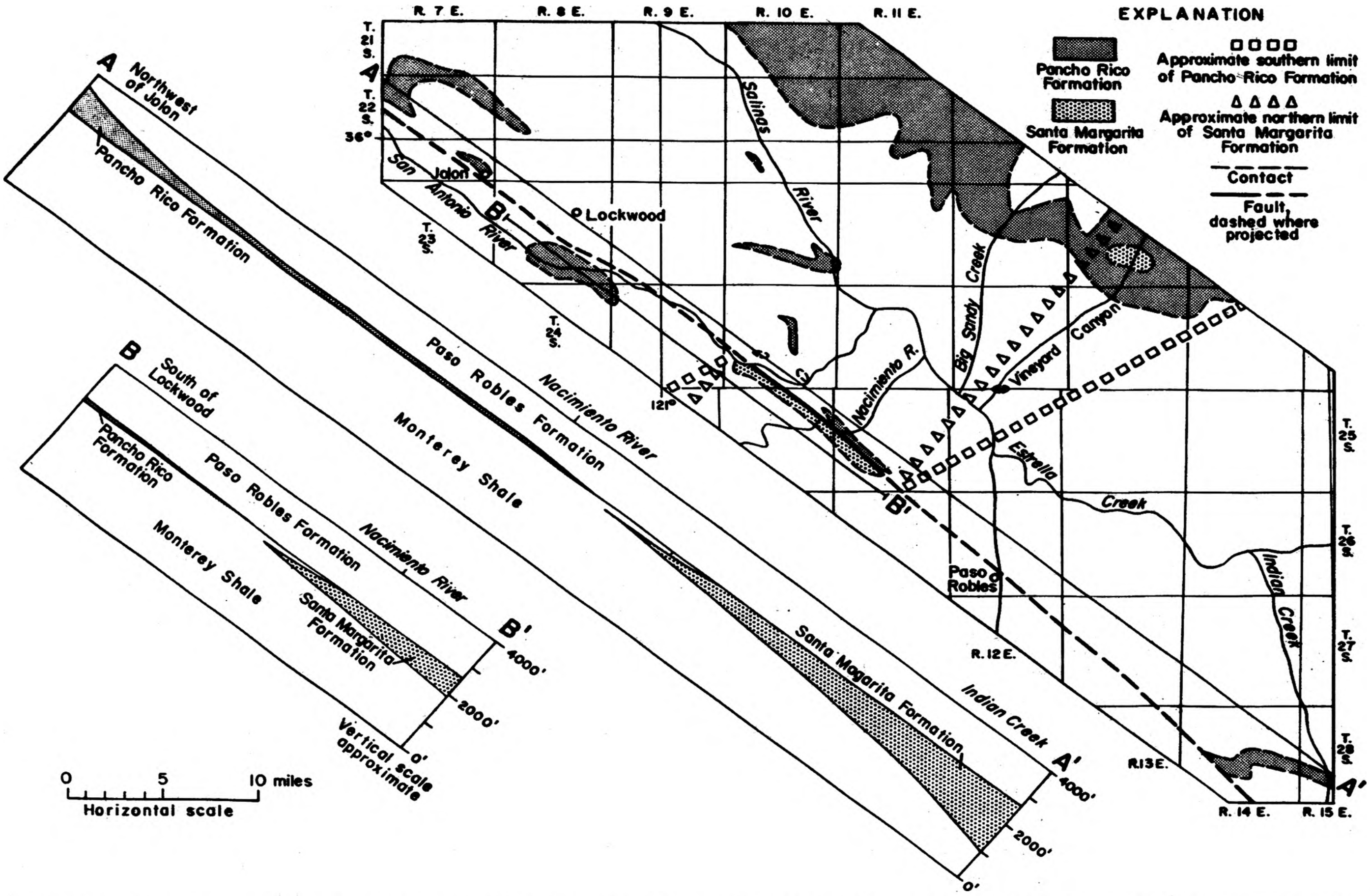

Fig. 6. Facies map and cross sections indicating about 11 miles right slip on fault in Salinas Valley. Longitudinal sections parallel to fault show diagrammatically the stratigraphic relations and lateral variation of the Monterey Shale and Santa Margarita, Pancho Rico, and Paso Robles Formations in the area. From Durham (1965, Fig. 2). Location shown on Figure 2.

Appraisal of either the major strike-slip or reversing and repeated, dip-slip hypothesis can be aided if we systematize our procedures, but as yet there has been very little work of this kind done in the Coast Ranges. Units such as the Butano Sandstone, San Lorenzo Formation, and Purisima Formation need to be singled out, and facies and isopach maps prepared. Because the slip of a fault is defined as the displacement of formerly adjacent points, and where unique facies-change lines and isopachs meet the fault piercing points are formed, such maps may allow us to solve the faults for slip, whether dip slip, oblique slip, or strike slip (Crowell, 1959; 1962). The use of such lines is essential when appraising major strike slip on a regional scale, for, if crustal blocks carrying their canopy of sediments have truly glided past each other, the direction of displacement will be pretty much parallel to the trace of the bedding against the fault. It is therefore quite conceivable that there has been considerable "regional trace slip" but with almost no discernible "dip separation". An example of such a study in the Salinas Valley has recently been presented by Durham (1965) on a northwest-trending fault parallel to and about 20 miles southwest of the San Andreas. The "lines" at the limits of deposition of two upper Miocene formations (Pancho Rico and Santa Margarita) are offset with right slip of about 11 miles (Fig. 6).

Both hypotheses involve intermittent movement during the Tertiary. At times of quiescence, or when displacement was by nearly pure strike slip so that there was no topographic relief across the fault (that is, no fault scarp), sediments were laid down across the fault trace. At such times, tectonic features other than the fault controlled the shape of the topography which in turn controlled the spread of sediment. Only in such a way can we picture successively greater displacements of successively older units back into time. For example, one of the best documented displacements involves the offset of the upper Miocene facies change between continental and marine rocks at the southern end of the San Joaquin Valley (Hill and Dibblee, 1953, p. 446; Hall, 1960). Here the facies-change lines and margins of paleo-environmental zones have been offset about 65 miles since the late Miocene. At the end of the Miocene, the San Andreas had a course oblique to the trend of mountains and valleys in much the same way as it trends today.

Vertical movement on faults, such as those of the San Andreas system, are documented where dated sedimentary breccia or conglomerate lie along the fault and have demonstrably been eroded from the high-standing side in the past and shed onto the adjacent low block. Several such situations are known in California on the San Andreas or one of its branches. In fact, at present, these examples provide some of the best evidence in documentation of large strike slip, because the conglomerates have been displaced laterally from their source area since deposition. This is particularly well shown on the San Gabriel fault in the Transverse Ranges where two accumulations have been offset about 20 miles since the late Miocene from their source areas (Crowell, 1952; 1962, p. 39). In both examples, sedimentary rocks older than the breccia-conglomerates are now preserved across the fault from the deposits which include boulders and blocks of older basement rocks; only by going laterally along the fault can suitable source areas, exposed at the proper time, be found. A similar situation occurs in the Temblor Range, now under study by G. L. Fletcher, where upper Miocene breccias were derived from across the San Andreas fault zone to the west. In that region at present, there is no appropriate source that was exposed at the proper time. More than 65 miles to the northwest, however, on the other side of the fault, the probable source area is located. The presence of such breccia deposits demonstrates that the faults have had a dip-slip component of displacement where one side has been depressed with respect to the other, although the principal displacement has been by right slip. On the San Gabriel fault, for example, the dip-slip component seems to have been about 2½ miles, whereas the strike slip has been about 20 miles since the late Miocene. This fault, by the way, shows a greater right slip for basement rocks; about 30 miles. In fact, on the San Gabriel and San Andreas in southeastern California, all rocks older than earliest Miocene show nearly the same displacement, so we can conclude that the faults originated in the early Miocene. In this region, the San Gabriel seems to have a total displacement of 30 miles, and the San Andreas of 130 (Crowell, 1962), totalling about 160 on the system. A large suite of similar rocks, (basement, sedimentary, and volcanic) with a remarkably similar history, appears to have been displaced.

The documentation for major strike slip on the San Andreas fault is, therefore, considerably more impressive for the southern half of the fault in California. For the northern half, which includes the stretch between the 37th and 40th parallels, only the younger rocks are known to be displaced laterally; the Merced Formation (upper Pliocene) in the Bay area studied by Higgins (1961) and the Santa Clara Formation (lower Pleistocene) in the Palo Alto quadrangle (Fig. 5). In this latter area, Dibblee (1966) states that right slip may be as much as 25 miles, inasmuch as debris within the unit now on the western side was apparently derived from a source directly across to the east at time of deposition but which is now found about 25 miles laterally displaced. With such evidence as this, supplemented by data from earthquakes and resurveys of triangulation nets, we can only at present assume that the San Andreas in the north probably has much the same type of movement as in the south. Mismatches in stratigraphic units across the fault, as shown in Figure 5, are probably the result of major strike slip, but we cannot consider the matter solved until sufficient stratigraphic studies have been undertaken. These studies must focus upon units that are sensitive to the geometry of strike slip in bedded rocks.

The age, or time of origin, of the San Andreas fault is another problem not yet solved. Two approaches seem to be available to us in striving for an answer: 1) to find the oldest sedimentary deposit containing debris unequivocally eroded from an ancient fault scarp that can be identified with the San Andreas, and 2) to plot the increasing displacement of cross-cut rocks with time until we find that all rocks older than a certain age are displaced the same, or maximum, amount. The oldest, coarse debris, within sedimentary units that are close to the San Andreas, are found in the Gualala Formation of very Late Cretaceous or Paleocene age (Durham and Kirk, 1950). These have not yet been sufficiently studied, however, to show that they were laid down at the base of an ancestral San Andreas fault scarp. Facies of rocks older than these appear to be clearly transected by the fault, which therefore must be younger.

By analogy with our knowledge of the southern part of the fault, it may well be that the northern stretch of the San Andreas is also no older than earliest Miocene. The answer will have to await the outcome of statewide comparisons of the stratigraphic sequences along the fault. Such comparisons can be expected to reveal data both on the age of the fault and on its total displacement.

Interpretations concerning the age of the fault are very much dependent on whether or not the San Andreas is indeed an intermittently active, right-slip fault of immense displacement. Under this concept, it will have brought together older terranes which were initially far distant. The contrast in stratigraphic units, as discussed here with reference to Figure 5, then finds ready explanation. The lateral changes in formations and unconformities can be conceived of as taking place gradually away from the terrane at hand and on the same side of the fault, and unit by unit changing laterally along the strike of the fault into the character of the correlatable unit preserved on the other side. In the case of the Palo Alto quadrangle (Fig. 5), an area which presumably stood "high" on the average through the Tertiary, as shown by thin units and several unconformities, may have been brought next to a region which through time was largely a "low" area with thicker and finer deposits and few unconformities. The historical or traditional interpretation of such a contrast in stratigraphic units, that involves intermittent dip slip, so far as age of the faulting is concerned, would place emphasis on the unconformities and the transgression across the fault of units directly above them. With regard to Figure 5, pre-Butano movement would be implied in order to bring the Franciscan complex next to the granitic basement, and the fault would be considered to have a pre-Eocene activity. With major strike slip, it is quite possible for the same relations to result from post-Eocene or later movements with no previous movements. This involves displacing a previously existing contact of some sort between the Franciscan and the granitic basement. Hill and Dibblee (1953) and Curtis and others (1958) have assumed a buried contact beneath the Great Valley between the Sierra Nevada granitic and metamorphic rocks on one hand and the Franciscan complex on the other that was subsequently offset many miles. From such data as that in Figure 5 and until we have better knowledge of the distribution of the Butano Sandstone and its facies, we might well achieve the contrast by post-Butano (or later) right slip alone and not require an additional episode of pre-Butano movement.

The early Tertiary in California was largely a time of crustal quiet compared to the tectonic events which fragmented the region into basins with broad intervening highs in the early Miocene. Paleocene deposition mainly followed patterns set in the Late Cretaceous except for local transgressions landward upon beveled older rocks, as along the Pacific coast near Monterey. The Eocene strata are widely but sparsely preserved in the Coast Ranges and are spread throughout the length of the Great Valley where they lie without much difference in degree of deformation on the Cretaceous. The region of the Sierra Nevada rose at this time so that its metamorphic and vein-bearing rocks were deeply eroded to give up gold ore which was then washed westward in Eocene streams. The auriferous gravels of these old streams have provided some of California's most valuable gold deposits. Farther west, sediment from these streams made its way down deep notches cut into the pile of sedimentary rocks flanking the sea to manufacture submarine canyons. These are now filled and preserved with later deposits; their existence demonstrates that submarine canyons, of the same grandeur as those in the seas today, were formed in the geologic past by a combination of tectonic and sedimentary processes and are not related to special events in connection with the Pleistocene and Recent. During the Oligocene, marine rocks were laid down locally in central California, but to the south in the Coast Ranges, vast blankets of red beds (Sespe Formation) were deposited.

In briefly summarizing the Tertiary tectonic history in central California, two major styles of deformation prevailed, but both are intimately related. The first and pervading style consists of widespread folding accompanied by dip-slip faulting and associated uplift of elongate ranges and concomitant depression of paralleling valleys. Locally the folding was severe, and beds are now vertical or overturned and at places truncated sharply by unconformities. Where folding was especially intense with incompetent rocks at depth, piercement structures were formed late in the Cenozoic, and mobile rocks, including serpentine, diapired surfaceward through the torn ends of enclosing strata. At other places, especially at the margins of high-standing blocks, downslope gravity structures formed. In contrasting regions, such as the Great Valley, there was relatively little deformation until at the end of the Tertiary and then only the margins were noticeably affected. The second style is actually a part of the first. Some crustal blocks are bounded or crossed by steep fault zones along which intermittent strike slip has taken place. Perhaps this displacement, accumulating during the later part of the Tertiary and less certainly before, has brought about lateral displacements exceeding 200 miles.

MESOZOIC TECTONICS

Central and northern California are underlain by vast expanses and thicknesses of Mesozoic rocks; sedimentary, volcanic, plutonic, and metamorphic. In a gross way, there are three types of terranes. First, on the east and north, in the Sierra Nevada and Klamath Mountains, are metamorphosed Upper Jurassic and older strata which have been strongly faulted and intruded by Jurassic and Middle Cretaceous plutons. Second, this "basement" terrane, deeply eroded, is overlain unconformably by an immense pile of Mesozoic sedimentary rocks with strata as old as Late Jurassic at the bottom. These strata belong to the relatively undeformed and unmetamorphosed Great Valley sequence and crop out primarily in a band along the west side of the Sacramento and San Joaquin Valleys. Third, the Franciscan complex underlies most of the central Coast Ranges and consists of deformed graywacke, mudstone, chert, volcanic rocks, and associated ultrabasics that range in age from Late Jurassic to Late Cretaceous. In addition, west of the San Andreas, the basement rocks are similar in many ways to those of the Sierra Nevada and Klamaths, and finally, along the coast, lies another strip of the Franciscan complex with strata of the Great Valley sequence. In the main, the problem is to find a tectonic explanation for the juxtaposition of these diverse rocks with their complex histories and nearly similar ages.

The rocks in the foothills of the Sierra Nevada, at the eastern margin of the Sacramento Valley, consist of metamorphosed graywacke, slate, metaconglomerate, metavolcanic rocks of several kinds, metachert, and other rock types which are now steeply dipping and deformed (Clark, 1964). The sediments infilled a late Paleozoic and Mesozoic geosyncline which on the east is now occupied by a series of granitic plutons; the Sierra Nevada batholith. Several formations in different fault blocks have been dated paleontologically as between the Callovian and early Kimmeridgian Stages, including the Oxfordian (Table 1). The total thickness of Jurassic strata in this region exceeds 15,000 feet. After deposition ceased in Kimmeridgian time (Late Jurassic), the strata were folded into a synclinorium, faulted, and metamorphosed. The folds and homoclinal sections have subsequently been transected by the distinctly later Foothills fault system (Clark, 1960). This system (Fig. 1) consists of nearly vertical, cataclastic zones containing steeply plunging minor folds and b-lineations, a fabric which suggests strike-slip displacement, but the sense and magnitude of displacement are unknown. One of the faults on the north is crosscut by granodioritic and quartz dioritic instrusions which have been dated isotopically at 131 and 143 million years or later Jurassic (Curtis and others, 1958). On the south, another strand of the system is crosscut by a lobe of the Sierra Nevada batholith which was presumably emplaced during the Middle Cretaceous.

Table 1

European Stages of the Upper Jurassic and Cretaceous Systems

Upper Cretaceous	Maestrichtian	
	Campanian	
	Santonian	
	Coniacian	
	Turonian	
	Cenomanian	
Lower Cretaceous	Albian	
	Aptian	
	Barremian	Neocomian
	Hauterivian	
	Valanginian	
	Berriasian	
Upper Jurassic	Purbeckian	Tithonian
	Portlandian	
	Kimmeridgian	
	Oxfordian	
	Callovian	

The Klamath Mountains are also composed largely of Paleozoic and Mesozoic rocks which have been metamorphosed and deformed, intruded by ultrabasic and granitic bodies, and then deeply eroded (Irwin, 1964). The youngest sedimentary rocks involved in this history are dated paleontologically as Late Jurassic (as young as middle Kimmeridgian). They consist of mudstone and graywacke and are very similar in lithology to strata of the same age in the Sierra Nevada. On the far northwest, near the Oregon-California border, Dott (1965) and Koch (1966) have succeeded recently in partly disentangling younger (Tertiary) deformations from at least two older ones in the Late Jurassic and Cretaceous. The Kimmeridgian and older beds were metamorphosed to phyllite and greenschist, and a westwardly, convex, arcuate structural grain, consisting of folded belts bounded by thrust and high-angle faults, was formed in the Late Jurassic. Irwin (1964) has speculated that some of these thrusts represent far-travelled plates riding on sheets of ultramafic rocks, largely serpentine, but most of the relations could perhaps as well be explained by tight folding and steep thrusting without immense displacement. These events are reasonably well bracketed in time, for, as in the Sierra Nevada, there are post-metamorphic and post-deformational intrusions which have also been dated as Late Jurassic. In both the Sierra Nevada and Klamath Mountains, the evidence in hand at present indicates a remarkable telescoping of tectonic events. In just a few million years, beginning in about mid-Kimmeridgian and lasting till mid-Portlandian time, eugeosynclinal sedimentation of mudstone and graywacke with some volcanics ceased, the whole was deformed and metamorphosed, intruded by ultrabasic and granitic rocks in succession, and then uplifted and deeply eroded, and finally subsided. In addition, in the Sierra, the Foothills fault system (a high angle system with presumed strike slip) predated the intrusions (Clark, 1960). This system, identified on the basis of its time and character of movement, has not yet been certainly recognized in the Klamath region.

At the northern end of the Sacramento Valley (Fig. 1), the Great Valley sequence of unmetamorphosed upper Mesozoic strata lies depositionally on the beveled Klamath and Sierra complexes just described. The base of this sequence has been dated paleontologically as Portlandian (Late Jurassic), and the sequence ranges upwards without significant stratigraphic break through most of the Cretaceous. This thick pile of graywacke, mudstone, and conglomerate totals a thickness of over 40,000 feet (Bailey and others, 1964, p. 123) and was deposited upon and transgressed across the eroded and subsided margins of the Sierra and Klamath regions. A cross section through these strata (Fig. 7), which are now folded into a broad syncline, shows that successively younger beds lap farther and farther to the east. At the eastern and northeastern edges of the Sacramento Valley, the overlapping Upper Cretaceous rocks lie directly upon a beveled basement surface. The locus of sedimentation has moved steadily eastward through time. Not only is this indicated by the cross section (Fig. 7) but by the fact that all 40,000 feet or so of the Upper Jurassic and Cretaceous strata are unmetamorphosed. Although the strata at the bottom of the pile are somewhat better indurated, they are not significantly different in mineralogy from similar rocks near the top. If the beds had been laid down in a simple subsiding trough which then overflowed at its eastern margin as it filled up, the rocks buried at 40,000 feet should show effects of metamorphism. It seems far more likely that at no time was the vertical column, which could exert lithostatic pressure at the base, greater than about a half of this thickness, or 20,000 feet. Incomplete data in hand suggest that, as the trough of sedimentation overlapped eastward, most of the sediment travelled into it from the north (Crowell, 1957, p. 995; Ojakangas, 1964).

The third type of Mesozoic terrane in central California, and by far the most perplexing, is the Franciscan. It is perplexing because everywhere that Franciscan graywacke, mudstone, conglomerate, chert, mafic and ultrabasic volcanic rocks, and other eugeosynclinal rocks have been studied, they are broken up and heterogeneously deformed. Folds and faults exposed in rare streamcuts and roadcuts display a complexity which cannot be mapped and followed elsewhere through the underbrush and beneath the mantle of thick soil. The majestic Redwood forests effectively obscure a great deal of geology, and unfortunately the complex does not lend itself to conventional stratigraphic attack or mapping. Beds or stratigraphic units cannot be traced sufficiently far enough across country to outline major folds or to determine structural grain. Moreover, the Franciscan rocks are particularly perplexing, because fossils and isotopic dates show a range in age from Late Jurassic to Late Cretaceous. These disturbed rocks are, therefore, largely coeval with those of the Great Valley sequence (part may be older) and at least in part with those of the Klamath Mountains and Sierra Nevada. The major problems are to discover: 1) the relations of the Franciscan to its adjoining coeval equivalents, 2) its environment and place of deposition before deformation, including the nature of the floor on which it was laid down and the character of the basin margins, and 3) the timing, style, and magnitude of the several deformations to which it has been subjected. All of these together, with their ramifications, constitute what is commonly referred

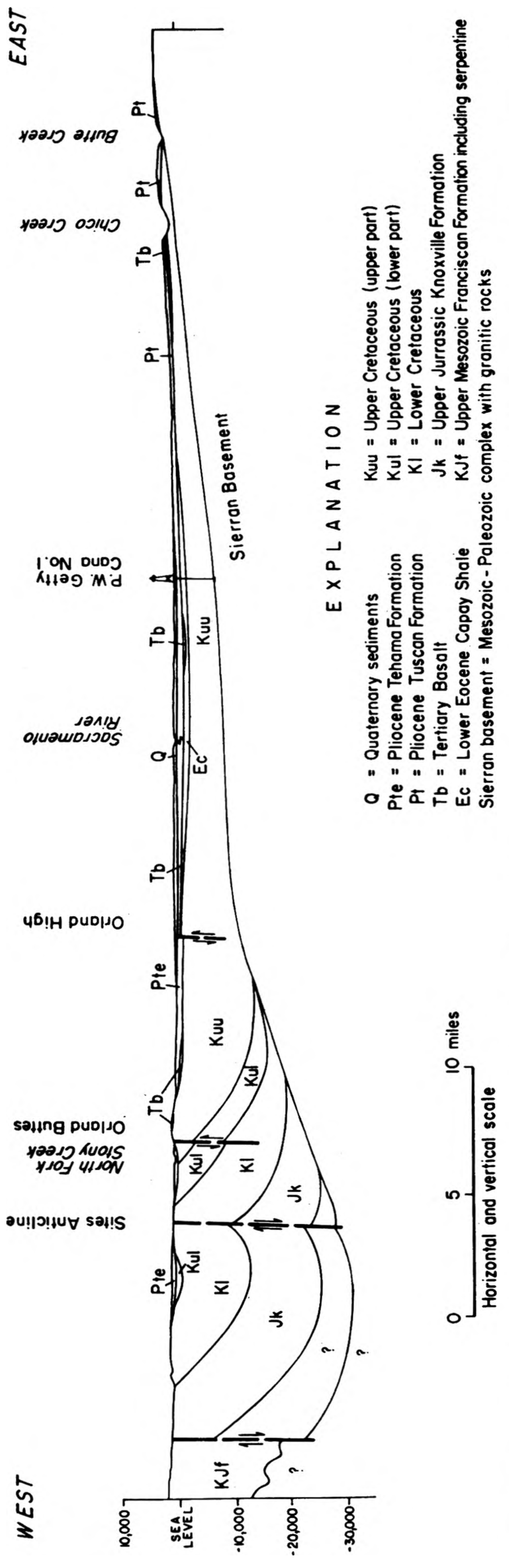

Fig. 7. Generalized cross section across the Sacramento Valley, California. Redrawn from Lachenbruch (1962, Pl. 3). Location shown on Figure 2.

to by California geologists as "the Franciscan problem". For those who wish to learn more of the Franciscan, the report by Bailey and others (1964) contains a wealth of information.

The mixture of rock types within the Franciscan complex includes those that are metamorphic as well as those that are not. The metamorphic types belong to the zeolite, blueschist, and eclogite facies (Bailey and others, 1964, p. 89-112; Ernst, 1965) with only rare representatives of other facies. Of special interest are the blueschist rocks which include jadeitized meta-graywacke and glaucophane schist in particular. Recent laboratory studies of mineral-stability relationships indicate that the blueschist rocks of the Franciscan must have been depressed to the neighborhood of 70,000 feet (Bailey and others, 1964, p. 111; Ernst, 1965). Deposition and downwarping took place so rapidly that heat flow from below, plus heat generated by radioactivity within the strata, was unable to reach normal steady-state conditions. An abnormally low temperature relative to pressure prevailed. The sediments at the bottom of the pile were not only depressed to these extreme depths very quickly—perhaps in a few million years—but they must also have been quickly raised again; otherwise they would have slowly heated up and been converted to the more normal greenschist facies. In this connection, studies throughout the Franciscan terrane of the K-feldspar content in graywackes (Bailey and Irwin, 1959) that were undertaken primarily to subdivide the complex on a mineralogic-stratigraphic basis show that the oldest part of the Franciscan is almost totally lacking in K-feldspar. These rocks would accordingly be expected to have had an abnormally low rate of heat generation due to radioactive decay. Tectonic inclusions of eclogite, also indicating great depth but higher temperatures, and masses of serpentine are also widespread. All of these data, bearing on the rate and depth of burial of the older Franciscan sediments and their rapid subsequent uplift, need to be fitted, with the age of the sediments and the structural occurrence of the metamorphic portions, into the tectonic history.

The broken up aspect of the Franciscan terrane is one of its distinctive characteristics. Almost everywhere blocks, lenses, masses, and slabs of most of the Franciscan rock types—ranging from unmetamorphosed graywacke to eclogite—lie jumbled in a sheared and finer matrix. Several different explanations for this pervasive mixing have been advanced, such as:

1) shearing in connection with thrust faults, with reverse faults, and with steep and deep, "shear zones"; 2) downslope sliding shortly after deposition or later around the margins of uplifted high areas (ordinary gravity structures), or on a giant scale over distances of many tens of miles (Hsu, 1966); and 3) deformation within diapir or piercement structures (Eckel and Myers, 1946; Bailey and others, 1964, p. 155). All of these processes have probably operated at one place or another, but some, if they can be proved, are capable of moving large masses for many miles and mixing them in the process. These powerful processes need to be investigated especially, for they may contribute most significantly to our understanding of the present tectonic framework. We need as well to search for criteria bearing on the timing of the processes. Downslope sliding not long after deposition lies at one end of the time spectrum. Pre-metamorphic, jumbled masses of conglomerate-breccia with slabs of graywacke and mudstone and pebbly mudstones have been recognized in the Franciscan. Impressive seafloor slumps occur in the Great Valley sequence as well, where masses with Early Cretaceous fossils were carried into Late Cretaceous sediments (Brown and Rich, 1960). At the other end of the time spectrum, some piercement structures were wholly or in part formed during Pliocene and Pleistocene deformation. Along the Diablo antiform (Bailey and others, 1964, p. 154), for example, Franciscan rocks with serpentine were squeezed upwards; around the margins of the piercement structure upper Tertiary beds stand steeply. In such cases, it is extremely difficult to differentiate shearing formed between slabs during late upsqueezing from that formed before, perhaps several times, in the long history of variable deformation that has affected the Franciscan.

The age of the Franciscan complex and its stratigraphic relations to the Great Valley sequence have puzzled several generations of geologists. Scarce but widely scattered fossils range in age from Late Jurassic (Tithonian) to Late Cretaceous (Campanian), a range which makes the Franciscan coeval with most of the Great Valley sequence. Some of the Franciscan is older than the Great Valley sequence in that locally it occurs beneath it, but at few places has an unequivocal depositional contact, conformable or unconformable, been demonstrated. Because the Franciscan also contains metamorphic rocks and graywackes with less K-feldspar—this mineral increases in abundance upward stratigraphically in both the Great Valley and Franciscan rocks—it is likely that the oldest Franciscan is older than the oldest Great Valley strata. Near the California-Oregon border, Dott (1965) has shown that some metamorphic rocks, which are Oxfordian but perhaps also in part Callovian and Kimmeridgian in age, are considered part of the Franciscan in California. Here there is a sharp break between an older metamorphic "Franciscan" below, with blueschist and greenschist facies rocks, and unmetamorphosed "Franciscan" above. The studies by Bailey and others (1964) in the California Coast Ranges suggest that, unlike the Sierra Nevada, Klamaths, and Oregon-border region, there is no sharp break between pre-Portlandian metamorphic rocks and post-Portlandian sedimentary rocks, but perhaps the break has not been recognized. Instead, the metamorphism seems to decrease gradationally upward from the maximum at the base of the immensely thick pile which was depressed deeply into the crust and then quickly raised. In the middle of the trough it may be that there was nearly continuous deposition, subsidence, metamorphism, and elevation, whereas on the margins sharp uplift and deep erosion took place in the late Kimmeridgian or early Portlandian. Some of the mafic volcanic rocks now found within the older parts of the Franciscan terrane may be uplifted parts of the basaltic floor on which the sediments were deposited. In summary, it seems an attractive working hypothesis to picture Franciscan deposition as beginning in the Callovian or Oxfordian in an offshore deepwater environment directly on the oceanic floor and continuing very rapidly with sharp downbuckling and followed immediately by rapid uplift.

The Late Cretaceous age (Campanian) of the younger part of the Franciscan complex poses quite another problem. The question here is whether deposition continued as a more or less orderly process, with some interruptions and minor structural events in the center of the Franciscan trough until the Campanian, or whether there were periods of dramatic thrusting and gravitational sliding on a grand scale so that much of the jumbled complex is allochthonous as has been recently advocated by Hsu (1966). Such mixing would have stirred younger blocks and lenses amongst older, all within a sheared matrix of young sediments, comminuted older sediments, serpentine, and volcanic rocks. Hsu has mapped and studied several Franciscan areas, including the type area around San Francisco, but especially the "western belt" along the coast near Estero Bay. He has been able to trace a sequence in the size of the blocks, "floating" in matrix, from small lenses and phacoids, easily studied in roadcuts and sea cliffs, to huge masses several miles across. Of particular significance are exposures which demonstrate an extensional fracture pattern rather than a compressional or shortening fabric. Graywacke beds at places have been pulled apart and the sequence thinned. In many ways, the terrane is similar to that of the Appennines of Northern Italy and the chaotic ground of the *argille scagliose* (Maxwell and others, 1964).

Hsu (1966) has studied and classified blocks on the basis of petrography, density, and metamorphism. Among his types, he recognizes pre-Portlandian chert, greenstone, and interbedded clastics; these pre-Portlandian rocks, he considers as the only true "Franciscan" rocks of the region. According to him, these strata were thrust westward from their counterparts in the Sierra Nevada during a Late Jurassic orogeny. The root zone would presumably lie buried but near the eastern edge of the Great Valley. Following the thrusting, strata correlative with the Great Valley sequence were laid down unconformably upon these disturbed rocks and across the region of the Coast Ranges, and deposition continued until about the middle of the Cretaceous. Gravity sliding on a huge scale then took place in the Late Cretaceous, and fossiliferous younger rocks were broken into slabs. Large masses (some several square miles in area and internally undeformed) of uppermost Jurassic and Lower Cretaceous rocks were carried on the back of chaotic Franciscan rocks which are both pre-Portlandian and younger. Although the bedding and slide surfaces were originally subhorizontal, they now stand steeply as the result of late Tertiary folding; in the Estero Bay region, a regional, nearly isoclinal syncline in Miocene rocks trends parallel to the coast a few miles inland. Hsu's documentation of gravity sliding on a grand scale is quite convincing, but it remains to be established how widespread it is through the Franciscan terrane as a whole, and from which direction and source the sliding came. In looking for a source for the slides, we should search for an area where the coeval Great Valley beds are not now preserved, and with regard to the melange in the coastal belt, offset 200 miles or so by Tertiary strike-slip movements. According to his concept, most of the Franciscan terrane shown on California maps is a tectonic mixture or melange of many Mesozoic rocks, some in stratigraphic order, but many not. The term "Franciscan" is therefore used in both a stratigraphic and a tectonic sense. Progress will be enhanced if these two usages are distinctly separated and standard stratigraphic sections established and named, even though they may be many and incomplete. Tectonic sheets need naming as well and given type localities so that as our knowledge increases we can make order out of what now is truly chaos. In the present paper, the term "Franciscan" is employed to include both the stratigraphic and tectonic usage.

Other workers in Franciscan terranes have found evidence of major thrusting. West of Stonyford, Brown (1964) has mapped a thrust which has carried beds of the Great Valley sequence westward for about 20 miles upon a "friction carpet" of Franciscan debris and serpentine. The thrust is the westward extension of the Stony Creek fault zone which for many miles separates the Great Valley beds from Franciscan rocks and is nearly everywhere followed by serpentine. Its straight course across rugged topography indicates that it is a high-angle fault dipping to the east and no doubt is one of the important faults in the central Coast Ranges. Inasmuch as Upper Cretaceous rocks in the vicinity are deformed nearly as much as other rocks in the upper plate, the time of thrusting may be Tertiary and distinctly later than the post-Portlandian thrusts postulated by Irwin (1964) in the Klamath Mountains and the Late Cretaceous gravity slides of Hsu (1966) in the Estero Bay region. Its steep dip and course northwestward along the margin of the Klamath region suggests that it may in part be the easternmost major strike-slip fault of the San Andreas system and tie in with the major Tertiary faults of Dott (1965) in southern Oregon. Other thrusts have been described by Marsh (1960) and Weaver (1949), but these are definitely Tertiary features. Of special interest are the Franciscan tracts in the northern Coast Ranges where the metamorphic grade increases upward from the bottoms of deep canyons to the tops of adjacent mountains (Irwin, 1960; Kilmer, 1961; Ghent, 1963), an arrangement that suggests either thrusting or an overturned section.

The pre-Jurassic tectonic history of coastal California is obscure. Here and there within the basement complex are patches of metasedimentary rocks which show that Paleozoic and early Mesozoic strata were laid down near what is now the continental margin. But tectonic episodes of the distant past have not as yet been disentangled from the subsequent record; fortunately they have only a minor bearing on the appearance of a tectonic cross section drawn today.

THE CONTINENTAL MARGIN

Our tectonic cross section ends in the floor of the Pacific Ocean where typical oceanic crust underlies water deeper than 12,000 feet. Here, data from seismic velocities, sporadic samples obtained by dredging and coring, and studies of oceanic islands lead to the conclusion that the Pacific floor consists of a 3- to 5-mile thickness of basalt, perhaps with some serpentine that overlies the Moho discontinuity and mantle. At a distance from shore, about a one-half mile thickness of unconsolidated sediment, mostly mud and calcareous ooze with some intercalated volcanic material, lies above the basalt. The oldest sedimentary rocks so far found in the Pacific are Middle Cretaceous (Albian) in age (Ewing and others, 1966), but samples are so sparse that older lithified strata beneath the veneer of unconsolidated sediments at places may well in time be discovered. Near the California coast, great aprons of modern and undeformed sediment extend westward from the base of the continental slope (Menard, 1955). These fans are composed of continental detritus that has been carried westward largely from the mouths of submarine canyons by undercurrents. The oceanic floor is, therefore, surprisingly thin and simple in structure compared to the nearby continent.

Off the coast of California, the Pacific floor (Fig. 2) is broken by several great faults which extend in an east-west direction and can be traced oceanward for over a thousand miles (Menard, 1955). The chief evidence for their existence is topographic; they are marked by straight and abrupt submarine escarpments that are among the more impressive long breaks in the earth's surface. Mason (1958), Vaquier (1959), and others have mapped and studied the distribution of linear magnetic anomalies in the region of these faults and have suggested that offset belts of anomalies show strike-slip displacements of several hundreds of miles. The origin of the magnetic anomalies and the significance of the apparent tremendous offsets along the fault zones is a most intriguing problem.

Dietz (1961) and Hess (1962) have suggested, in order to explain: 1) the apparent youth of the basaltic ocean floor, 2) the lack of a thick sedimentary veneer upon it, and 3) the tectonic pattern, that ribbons of new lava are emplaced along the axes of mid-ocean ridges, presumably at the point of uprising of convection currents in the mantle. New sea floor is thus manufactured at the ridge crests which forces outward the floor just made; the sea floor, therefore, in general spreads from the mid-ocean ridges toward the adjacent continental margins. Vine and Matthews (1963) have advanced the hypothesis that the linear belts of magnetic anomalies are the result of periodic reversals in the earth's magnetic field taking place during this nearly continuous manufacture of new ocean floor by the intrusion and outpouring of basalt. This process would account for the long linear anomalies, but each anomaly would have a different age. Those near the axis of the mid-ocean ridge would be younger than those at a distance. In using the offset of such anomalies to measure strike slip on the Pacific fault zones, the presumption is that all of the displacement is younger than all of the anomalies. With our present state of knowledge, such immense displacements in relatively short intervals of geologic time are unacceptable. Talwani and others (1965) prefer an explanation which assumes that the fault zones are ancient "zones of weakness" and that the belts of lava with their magnetic anomalies have been emplaced since their origin. They conclude that the apparent offsets in crests of mid-ocean ridges and in anomalies are the way they are, perhaps because they were born that way.

This digression into ocean-floor tectonics has seemed desirable as background for discussing the boundary between the ocean and continent off the California coast. The boundary is so abrupt (Fig. 1) that a diffuse and steep fault zone seems required to separate the thick and ancient continental rocks from the thin and presumably much younger oceanic floor. The contrast is not limited to the crustal rocks only, but the upper mantle below the Moho is somewhat less dense under the continents where it may consist of plagioclase peridotite rather than peridotite as under the oceans, with a gradational zone between (Thompson and Talwani, 1964; Talwani and others, 1965). The Mendocino and Murray fault zones, although exceptionally prominent on the ocean floors, are far less conspicuous east of the continental edge. The Mendocino offsets the shelf and slope to the right for about 40 miles along the Gorda Escarpment near where the San Andreas system passes out to sea. Although the Mendocino zone cannot be followed farther east in detail, it lines up with the northern ends of the Sierra Nevada and Great Valley, and with the southern edge of the Cascadian lava fields. With regard to the Murray fault zone, beyond much question, there must be a genetic connection between it and the Transverse Ranges; again the connection seems a gross one as individual faults have not yet been traced directly from the continent into the ocean floor. At present it seems best to consider the oceanic fault zones as features of the mantle which pass beneath the continental plate. When the resolving power of our seismic methods has improved, we may be able to map them on the basis of contrasts in the elastic properties of the "anomalous" upper mantle. The faults are sharp and clear beneath the oceans, because here the crust is exceptionally thin and young and can be considered essentially as the surface expression of the top of the mantle.

These considerations suggest that the continental plate is nearly uncoupled from the mantle and the ocean basins; both at the base of the plate and at its western margin there may be a diffuse, distributive fault zone. Strike-slip fault zones, such as the Nacimiento, San Gregorio, and others farther south, may emerge and converge from within the continent and enmesh to make a master strike-slip fault at the edge of the plate (Crowell, 1965). At the same time, the major strike-slip movements of more than 200 miles on the San Andreas system imply a partial separation or décollement of surface rocks from those at depth. The hypothesis, therefore, seems attractive that western California is now undergoing a fragmentation or breaking up on major strike-slip faults; a process that seems to have started in the mid-Tertiary. In fact, the peninsula of Baja California may have drifted northwestwards from the mainland of Mexico as part of this process (Carey, 1958; Hamilton, 1961) and may have brought the Gulf of California into existence. The same process probably originated the present-day Great Valley of California and especially the San Joaquin Valley which during the Tertiary received a great thickness of sediment. Basins have developed between crustal fragments as they have moved apart or as the plastic crust was thinned during such movements. High areas and mountains have developed, under the basic control of isostasy, where blocks between faults were thickened by compression or by the addition of material at depth (Gilluly, 1963). At places the plastic crustal plate, subject to movements from below, has been drastically thinned so that deep "holes" have formed and migrated horizontally through time. Sediment filling in these moving holes has transgressed laterally, as in the case of the Great Valley sequence in the Sacramento Valley and deep late Tertiary basins in southern California. Because this scheme of tectonics is largely confined to the continental plate—though no doubt propelled by movements in the mantle below—the major strike-slip faults, like the San Andreas, do not extend oceanward significantly beyond the limit of continental rocks. On Figure 1, they are shown as well marked solid lines in the upper part of the crust. These lines become more diffuse but probably stronger at depth and then extend into the upper mantle only a short distance. The Moho is probably both a compositional and phase-changing discontinuity at different places or perhaps a combination; it may be near a tectonic discontinuity or distributive movement zone as well.

SUMMARY

Western California, as part of the Cordilleran mobile belt, has been the scene of nearly continuous deformation and sedimentation since the middle Mesozoic. Until near the end of the Jurassic, the region lay at the continental edge and was the site of a deep eugeosyncline. Rapid downward movements, accompanied by voluminous sedimentation and outpourings of basalt, carried strata to depths of about 70,000 feet where the deeper portions were metamorphosed to the blueschist facies and then very quickly elevated again. Following a possible episode of great thrusting, thick sediments were again deposited during the latest Jurassic and Early Cretaceous. At times in the Cretaceous, thrusts and immense gravity slides perhaps displaced strata within the geosyncline and imposed a widespread jumbled structure upon the Franciscan rocks. Widespread clastic sedimentation continued during the latest Cretaceous and early Tertiary. This was gradually followed by fragmentation of the region into mountain blocks and basins accompanied by both broad and sharp folding and dip-slip faulting. Major strike-slip faults developed and moved intermittently through time, so that at present some, like the San Andreas, have lateral displacements of as much as 200 miles. California today is still undergoing deformation which is a combination of compression resulting in the elevation of mountains and the depression of basins in association with superimposed strike-slip faulting. In contrast, the ocean floor to the west is thin, young, and simple.

Great latitudinal faults, sharply marked in the Pacific, extend eastward beneath the continental plate but are probably largely features of the upper mantle. The ancient and complex continental plate possesses its own tectonics and is probably separated from both the ocean floor and the mantle by broad distributive movement or fault zones.

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