QUATERNARY OF THE CALIFORNIA COAST RANGES

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Movements of the earth's crust have dominated the Quaternary history of the California Coast Ranges, and warping, faulting, and vulcanism have produced the topographic patterns that today characterize this province. Along the coast, marine terraces record the interplay between orogenic processes and climatically induced fluctuations of sea level.

The Coast Ranges southward from San Francisco Bay consist of a series of parallel, linear ranges, up to 40 miles wide and 5,800 feet high, separated by structural depressions from 1 to 10 miles wide, lying at elevations near sea level. Northward from San Francisco Bay the several ranges merge into a broad, nearly continuous highland with elevations up to 8,000 feet, but a number of equidimensional to elliptical structural basins occur within this highland. Linear structural elements within the Coast Ranges trend obliquely to the trend of the Coast Ranges as a whole (pl. 1).

The principal elements of the Quaternary history of these ranges are recorded by sedimentary strata, marine terraces, and drainage anomalies. The history of the southern ranges is documented by rather extensive sedimentary deposits of Pliocene and Pleistocene age. In the northern ranges, the stratigraphic record is less complete, but anomalous drainage patterns are much more conspicuous. Glacial effects are recorded only on a few isolated peaks in the northern Coast Ranges.

STRATIGRAPHY

Deposits of late Pliocene and Pleistocene age are mainly slightly consolidated gravels, sands, and silts of local derivation with some interbedded clays, marls, and freshwater limestones. Most of the strata are of continental origin, except for those adjacent to the present coast. Fossils are sparse in the continental strata, and the ages of many of the continental deposits are known only from their relations to older rocks. Radiometric dates obtained from volcanic rocks intercalated with the sediments are beginning to fill in some blank places. Locations, distributions, and ages of units referred to in the following discussions, together with selected references are provided in figure 1 and table 1. Deposits discussed in this article are referred to provincial ages, wherever possible, rather than to European epochs, because any given fossil assemblage can be referred much more precisely to provincial ages or stages than to classic European ages. Further, the absolute ages of provincial land mammal ages are known much more precisely than are those of the European epochs (see fig. 2). Where primary sources have referred fossil assemblages to European ages, I have followed the original usage, even though this procedure introduces an unnecessary uncertainty into the age assignment.

The widely accepted notion of a major mid-Pleistocene orogeny in the California Coast Ranges that stemmed from study of the Tulare and Paso Robles Formations in major oil fields seems to be overemphasized. These units are conformable on older strata in the structural depressions of the San Joaquin and Salinas Valleys, where the major oil fields occur. On the flanks of the ranges, however, these strata overlap older Tertiary units with profound angular unconformity and rest on Mesozoic rocks. The pattern of unconformities (see fig. 1) indicates that the "mid-Pleistocene orogeny" was but one unexceptional pulse in an orogeny that began in Miocene time; subsequently, the ranges have risen repeatedly while the basins have rather steadily subsided.

Deformed strata of Blancan and Irvingtonian age occur in the vicinity of the structural depression of San Francisco Bay and its extension southeastward along the San Andreas fault (fig. 1 and table 1, localities 2, 3, 5, 6, 9, 10, and 12). The Irvington Gravels (no. 3) are the type locality for the Irvingtonian land mammal age (Savage, 1951). The Merced Formation (no. 5) is marine through its lower 4,500 feet, and predominantly nonmarine through its upper 500 feet. The heavy minerals of the lower, marine section are characteristic of local source rocks. About 100 feet above the marine-nonmarine transition the heavy minerals abruptly change to a suite like that now carried by the Sacramento-San Joaquin River system which drains the Sierra Nevada. Hall (1965) interprets this change to represent the inception of drainage from the Central Valley through San Francisco Bay. Marine megafossils below this change in the heavy minerals correlate with the San Joaquin Formation, which is at least in part of Blancan age. About 300 feet above the mineral change occur teeth of *Mammuthus*, of Irvingtonian age. A few tens of feet above the *Mammuthus* locality occurs a hornblende-bearing tuff which has been dated at 1.5 m.y. by the K-Ar method.

The Clear Lake Volcanic Series consists of basalt, dacite, and obsidian. The older eruptives include deformed basalt that is interbedded with the upper Cache Beds of lower Pleistocene age. The youngest features include undissected flows, domes, and cinder cones.

Photo 1. View east across a section of the central Coast Ranges, climaxing in Mount Diablo. Photo by Commercial Photo and View Company, courtesy East Bay Municipal Utility District.

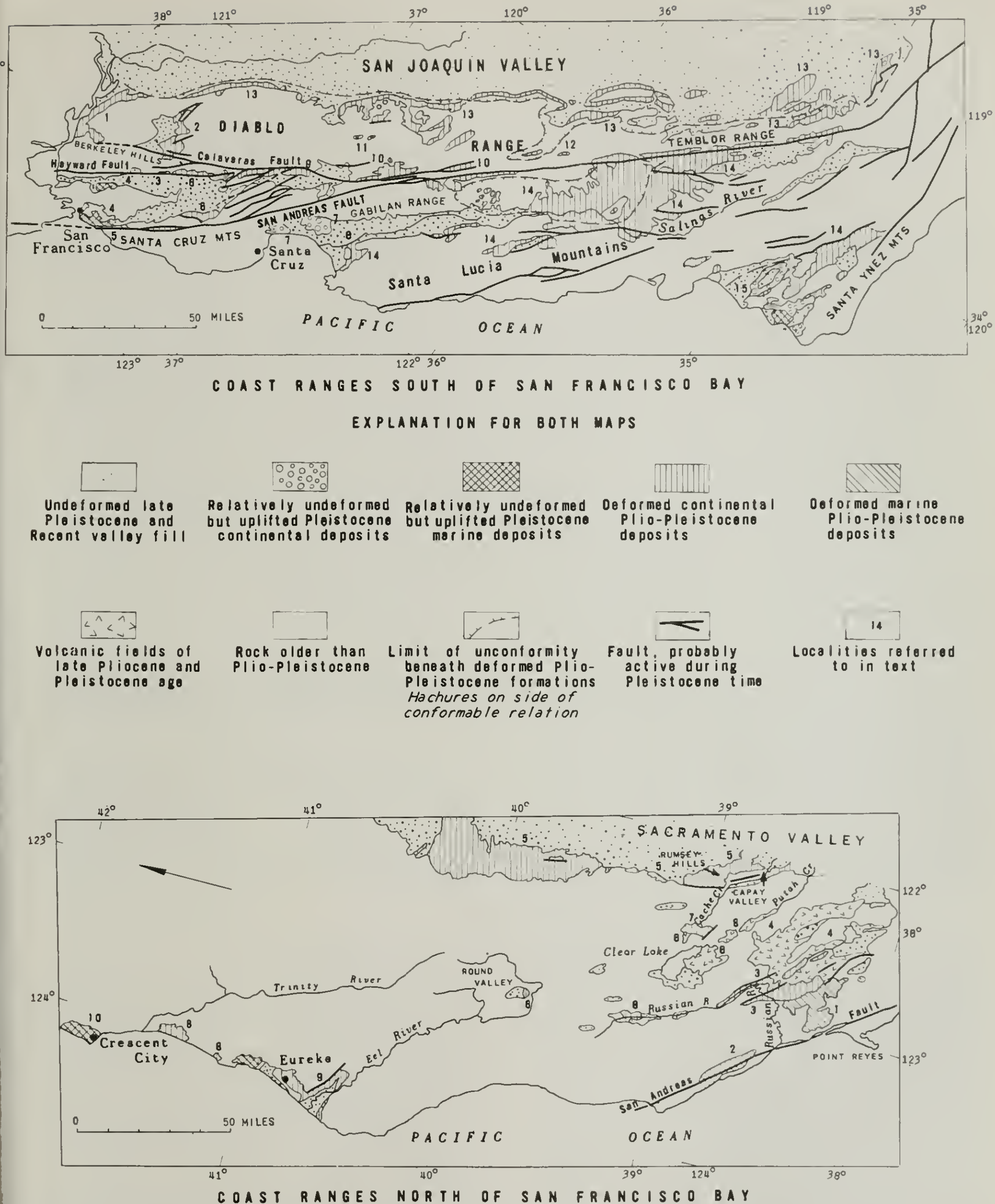

Figure 1. Geologic maps of the Coast Ranges north and south of San Francisco, showing late Pliocene and younger rocks, surfaces on which they were deposited, and faults believed to have been active during the Pleistocene. Maps also show localities referred to by numbers in the text.

Table 1, Part A—Table of Late Cenozoic formations in the Coast Ranges south of San Francisco Bay

Locality	Formation	Age from fossil or physical evidence	Relation to older rocks	Reference
1	Wolfskill (Tehama)	Blancan	Unconformable on Pliocene	Weaver, 1949; Savage, 1951, p. 217; Taliaferro, 1951
2	Livermore Gravels	Late Pliocene to Irvingtonian	Unconformable on middle Pliocene	Savage 1951, p. 284; Hall, 1959, p. 32
3	Irvington Gravels	Irvingtonian	Unconformable on upper Miocene	Savage, 1951, p. 276; Hall, 1959, p. 32
4	Various formations in San Francisco Bay area	Rancholabrean and younger	Conformable(?) on lower Pleistocene. Unconformable on Tertiary and older	Lawson, 1914; Louderback, 1951; Trask and Rolston, 1951; Radbruch, 1957; Schlocker and others, 1958
5	Merced	Late Pliocene and Pleistocene; Irvingtonian near the top	Unconformable on Mesozoic	Glen, 1959; Hall, 1965
6	Santa Clara Gravels	----	Unconformable on lower Pliocene	Branner and others, 1909; Lawson, 1914; Cummings, Touring, and Brabb, 1962, p. 213
7	Aromas Red Sands	----	Unconformable on upper Pliocene	Allen, 1946, p. 43
8	Alluvium of Salinas Valley	----	Conformable(?) on lower Pleistocene	Woodford, 1951
9	Packwood Gravels	----	Faulted against Mesozoic	Crittenden, 1951, pl. 1
10	San Benito Gravels	Blancan(?)	Unconformable on upper Pliocene	Wilson, 1943, p. 245
11	Peckham	----	Unconformable on Miocene(?)	Leith, 1949
12	Hans Grieve	Late Pliocene and Pleistocene	Unconformable on middle Pliocene	Rose and Colburn, 1963, p. 44
13	Tulare	Blancan, Irvingtonian, early Rancholabrean(?); 600,000 yrs. at base of upper third	Conformable on Pliocene in San Joaquin Valley; unconformable on Tertiary and Mesozoic on east flank of the Diablo Range	Woodring and others, 1940, p. 14; Taliaferro, 1943a, p. 147; Huey, 1948, p. 49; Long and Carpenter, 1963; Carpenter, 1965
14	Paso Robles	----	Conformable on lower Pliocene in Salinas Valley; unconformable on Miocene to middle Pliocene in the ranges	Schombel, 1940, p. 33; Taliaferro, 1943a, p. 147; 1943b, p. 460; Durham, 1963, p. Q21; Gribi, 1963a, p. 16; Jennings, 1958; Jennings and Strand, 1958
15	Orcutt Sand	----	Unconformable on Paso Robles Formation	Woodring and Bramlette, 1950, p. 51; Dibblee, 1950, p. 50; Upson and Thomasson, 1951, p. 39

Mount Konocti is an almost perfectly preserved dacitic strato-volcano, about 2,700 feet high. Numerous hot springs and solfataras are still active.

Deformed continental strata occur around the flanks of eight small structural basins in the central part of the northern Coast Ranges. These deposits are unfossiliferous, but their stratigraphic and structural relations, and degrees of consolidation and deformation are similar to those of the Cache Beds and of continental sediments associated with the Sonoma Volcanics of Blancan age. That these valleys are downwarped structures is clearly shown by the fact that alluvial fills extend as much as 1,000 feet below the lowest part of the bedrock rims.

Late Quaternary deposits that fill the centers of many of the structural valleys are essentially undeformed. Although in the centers of the valleys they may be conformable on older Pleistocene strata, around the margins they lie unconformably on lower Pleistocene or yet older strata. These deposits are best known in the San Francisco Bay area, where they are important for engineering purposes, and in Salinas Valley, where they are important aquifers. In both places marine strata alternate with nonmarine strata, probably representing fluctuations of sea level corresponding to glacial and interglacial periods. The structural depression at San Francisco Bay existed before these late Pleistocene fluctuations; the present flooding

Table 1, Part B—Table of Late Cenozoic formations in the Coast Ranges north of San Francisco Bay

Locality	Formation	Age from fossil or physical evidence	Relation to older rocks	Reference
1	Merced	Late Pliocene	Unconformable on Mesozoic	Johnson, 1943; Weaver, 1949; Travis, 1952; Gealey, 1951; Higgins, 1952; Stirton, 1952
2	Ohlson Ranch	Middle and late(?) Pliocene	Unconformable on Mesozoic	Higgins, 1960; Peck, 1960
3	Glen Ellen and Huichica	----	Unconformable on Sonoma Volcanics	Weaver, 1949
4	Sonoma Volcanics	Blancan, 3.4 m.y.	Unconformable on middle Pliocene and older	Axelrod, 1944, 1957; Weaver, 1949; Travis, 1952; Cardwell, 1958; Kunkel and Upson, 1960; Koenig, 1963; Evernden and James, 1964
5	Tehama	Blancan, 3.3 m.y.	Unconformable on Cretaceous	VanderHoof, 1933; Stirton, 1936; Anderson and Russell, 1939; Evernden and others, 1964
6	Clear Lake Volcanic Series	Pleistocene and Recent	Unconformable(?) on Sonoma Volcanics	Anderson, 1936; Brice, 1953
7	Cache Beds	Pleistocene in part	Unconformable on Eocene	Anderson, 1936; Brice 1953; Upson and Kunkel, 1955
8	Deformed unfossiliferous continental deposits	----	Consolidation and stratigraphic relations similar to Cache, Glen Ellen, and Huichica Formations	California Div. Water Resources, 1958
9	Carlotta	Early Pleistocene(?)	Conformable on upper Pliocene	Lawson, 1894; Ogle, 1953
10	St. George	Early Pleistocene	Unconformable on Mesozoic	Diller, 1902; Maxson, 1933; Back, 1937

of the Bay resulted from post-glacial rise of sea level rather than from Recent subsidence (Louderback, 1951).

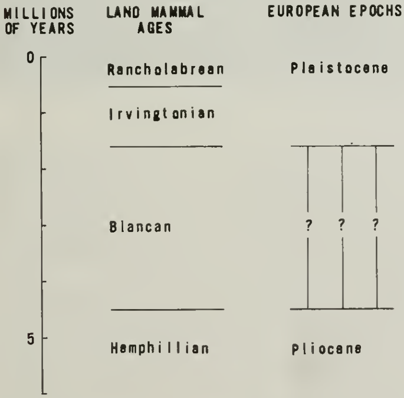

Figure 2. Duration of North American land mammal ages as indicated by radiometric age determinations. Adapted from Evernden and others, 1964, with additional data from Janda, 1965, and Carpenter, 1965.

STRUCTURE

The latest increments of Quaternary deformation have been graphically recorded by surface rupture on the Hayward fault in 1868, by right-lateral displacement of as much as 21 feet on the San Andreas fault in 1906 (Tocher, 1959), and now by continuing creep without accompanying seismic effects along the San Andreas fault south of Hollister (Tocher, 1960) and along the Hayward fault in Berkeley (Cluff 1965; Radbruch, 1965). The net lateral movement through Quaternary time is hard to assess. Russell (1926, p. 509) noted that stream valleys on the west side of the Berkeley Hills are apparently offset as much as 600 feet in a right-lateral sense where they cross the Hayward fault. Hinds (1952, p. 160) inferred as much as 3,000 feet of right-lateral displacement on the San Andreas fault from apparent offsets of streams. Hill (1952, p. 96) noted that Pleistocene gravels with contrasting composition are juxtaposed across the San Andreas fault on the west side of the Temblor Range; from this juxtaposition he inferred several miles of right-lateral displacement in Pleistocene time.

In the southern Coast Ranges, immediately adjacent to the active regional faults, Pleistocene strata are intensely deformed, and overthrust faults have been reported from several places (Crittenden, 1951; T. W. Dibblee, oral communication, 1964). Low-angle over-

Photo 2. Aerial view of The Geysers, northern Coast Ranges. *Photo courtesy Pacific Gas and Electric Company.*

thrusts occur on the east side of the Temblor Range, but these seem to be large gravity slides (Arnold and Johnson, 1910; Taff, 1933; Hudson and White, 1941; Simonson and Krueger, 1942).

Away from the active regional faults deformation was concentrated around the flanks of the ranges. For example, at the boundary between the Diablo Range and the San Joaquin Valley, the Tulare Formation, including beds 600,000 years old, is sharply flexed (Carpenter, 1965); in the San Joaquin Valley to the east of this flexure, and in the Diablo Range to the west, strata of the same or greater age are flat lying or, at the most, broadly warped and cut by small faults (Bailey and Myers, 1942; Leith, 1949). Similarly, in many places along the east side of the Santa Lucia Range the angles of dip and amplitudes of structures in the Paso Robles Formation are much greater than they are in strata of the same age within the range. These ranges appear to have risen vertically, with movements concentrated on marginal flexures or faults, with only broad warping and minor faulting within the ranges.

While the ranges rose the valleys subsided. In Salinas Valley continental sediments occur to depths of 3,000 feet below sea level (Gribi, 1963a, p. 76). In Santa Clara Valley, south of San Francisco Bay, freshwater molluscs and peat have been found in alluvium 300 feet below sea level.

To a fair first approximation, then, generalized contours on the land surface of the Coast Ranges south of

San Francisco Bay correspond to vertical movements of these ranges during Quaternary time. No clear geometric relation of these vertical movements to the regional strikeslip faults is apparent. The regional faults do not bound the vertically moving crustal blocks; rather, they cut diagonally across some, parallel others. There is no necessary mechanical relation between the vertical and lateral movements.

In the north Coast Ranges the stratigraphic record of Quaternary deformation is less extensive. Here, too, however, the intensity of deformation clearly varied from place to place. The Merced and Ohlson Ranch Formations along the coast are broadly warped, but the Sonoma Volcanics, with which the Merced Formation interfingers, are more intensely folded and faulted. Along the east side of the north Coast Ranges the Tehama Formation in some places (for example, Rumsey Hills) is folded into anticlines and faulted; elsewhere it is essentially flat lying. Near Eureka the Carlotta Formation and underlying Pliocene strata have been folded into a syncline, the flanks of which are locally overturned and overthrust by Cretaceous strata. The various alluviated valleys are basinlike downwarps.

At the turn of the century A. C. Lawson (1894) and J. S. Diller (1902) postulated a series of peneplains in the north Coast Ranges that were supposed to have been cut during pauses in the bodily uplift of the ranges in Cenozoic time. Wahrhaftig and Birman (1965) have shown that the gipfelfluhr (topographic surface generalized from summit altitudes) does not have the regularity that one would expect of a peneplain. Deformation of Pliocene and Pleistocene strata shows that these ranges were complexly deformed rather than uplifted as a single unit.

MARINE TERRACES

Multiple levels of marine terraces occur in many places along the coastline. These terraces are discontinuous, and none can be traced for more than a few miles. Terraces are specially well developed at Santa Cruz; Bradley (1957) showed that each of these terraces was cut during a period of rising sea level and that the veneer of marine strata was deposited during a decline in sea level.

Wahrhaftig and Birman (1965) studied the elevations of terraces along the entire length of the Coast Ranges. Locally remnants of terraces with pholad borings and marine strata occur at elevations as high as 900 feet. The higher terraces are moderately deformed; the elevations of their shoreline angles vary by as much as a few tens of feet per mile parallel to the coast (see also, Alexander, 1953; Bradley, 1965). The lower terraces are less deformed but even those vary in elevation by as much as a few tens of feet in a few miles.

Even the highest marine terraces appear to be of late Pleistocene age. Near the Santa Ynez River marine terraces more than 700 feet above sea level are cut into folds involving lower and middle Pleistocene strata. The lowest terrace (100 feet) at Santa Cruz has been dated by Blanchard (1963), using experimental U, Th, Ra methods, as about 110,000 years, hence probably of Sangamon age.

The extreme elevations of the higher terraces and lateral variations in elevations of individual terraces record uplift and warping of the mountains as well as eustatic changes of sea level. The late Pleistocene age of all terraces combined with progressively greater deformation of the higher terraces indicates that deformation has been more or less continuous throughout the later Pleistocene.

There is a puzzling lack of evidence of pre-Wisconsin high sea levels in the interior valleys. The youngest Pleistocene terraces and marine deposits on San Francisco peninsula have no counterparts on the east side of San Francisco Bay. Well-developed terraces on the coastal side of the Santa Lucia Mountains have no counterparts on the Salinas Valley side; further, the deposits within Salinas Valley are almost entirely continental, with only minor marine incursions.

DRAINAGE PATTERNS

Drainage patterns throughout the Coast Ranges show clear evidence of crustal deformation. In the headwater areas in the ranges the patterns are markedly subsequent, with streams finely adjusted to the relative erodability of the bedrock. These patterns were probably established on islands in the mid-Cenozoic seas. As the seas withdrew, as ranges rose and depositional surfaces were tilted, younger increments of drainage were added downstream. In some areas consequent patterns developed, with rivers flowing down the dip of inclined strata, or along the troughs of synclinal structures, or across prograding deltas. In some places crustal movements defeated and reversed earlier drainages; elsewhere drainages maintained their courses across intervening structures and markedly antecedent patterns developed. Defeated patterns are most apparent in the southern ranges where the climate is now dry and volumes of rivers are small. Antecedent patterns are conspicuous in the moist northern ranges where the rivers are large.

Defeated drainages in the southern ranges can be inferred from comparison of physical features of Plio-Pleistocene strata with the pattern of the present drainage. The distribution of heavy minerals and the configurations of sedimentary structures in the extensive Paso Robles Formation at the southeastern end of Salinas Valley indicate that these strata were deposited by streams flowing southeastward, across the present Temblor Range, into the San Joaquin Valley (J. Galehouse, oral communication, 1964). The Nacimiento and San Antonio Rivers, two southeastward-flowing streams in the Santa Lucia Mountains, were apparently headwater tributaries of this drainage system. These

Photo 3. View southeast along San Andreas Fault (Tomales Bay). Bodega Head in foreground. Northern Coast Ranges.

strata of the Paso Robles Formation are now being eroded by the Salinas River, a consequent stream flowing northwestward along a structural trough. Apparently the Plio-Pleistocene drainage was defeated by a combination of the rise of the Temblor Range, westward tilting of the Gabilan Range, and subsidence of Salinas Valley. The upper Salinas River has captured the headwater tributaries of the early drainage. In the Diablo Range the San Benito Gravels (Griffin, Stanford Univ., Student Research Project), and probably also the Hans Grieve Formation, were deposited by eastward-flowing streams in Blancan(?) time; they are now being eroded by westward-flowing streams.

Antecedent patterns in the north Coast Ranges are shown by rivers with alluviated headwater basins, some with thousands of feet of fill, and deep, downstream bedrock gorges. The headwaters of Cache Creek, for example, are in the deeply alluviated basin of Clear Lake; downstream from the lake Cache Creek flows through a deep gorge across a ridge of Cretaceous rocks; below the gorge it becomes a consequent stream in Capay Valley, which is a syncline in the Tehama Formation. Putah Creek flows through two alluviated valleys and across two bedrock ridges before it enters the Sacramento Valley. The Russian River flows through a string of alluviated structural basins and intervening gorges, enters the north end of a plain that declines toward San Francisco Bay, then turns westward to follow a deep gorge through a bedrock plateau to the ocean. Higgins (1952) has shown that the river prograded its way to the west as the sea withdrew, maintaining its course across the uplift that developed subsequently. The Middle Fork of the Eel River makes almost a complete circuit around the alluviated structural depression of Round Valley but does not flow into the valley—even though the base of the alluvial deposits in the valley is several hundred feet below the bedrock channel of the river. Apparently the course of the river was established before Round Valley subsided; gravels of presumed Plio-Pleistocene age have been warped around the edge of Round Valley.

Estuaries and thick alluvial deposits along the lower courses of the larger rivers indicate that they excavated canyons that were graded to a sea level about 300 feet below the present level (Louderback, 1951; Higgins, 1952; Evenson, 1959). Upson (1949) showed that along the southern part of the coast these canyons are cut through the lowest marine terrace, hence they are of Wisconsin age. Studies of beach and offshore sands by Cherry (1964) and Minard (1964) have shown that much of the sand on the continental shelf was transported along a shoreline that was several miles west of the present shore.

DATING THE OROGENY

Deformed strata, marine terraces, and drainage anomalies all attest to the recency of tectonic activity in the Coast Ranges. The pattern of unconformities indicates that this activity began in Miocene time and occurred in a series of pulses, the intensity of which varied from place to place and time to time. Only in the areas of the major oil fields did the most intense pulse come after deposition of early Pleistocene strata. Progressively greater deformation of the older marine terraces indicates that deformation continued more or less steadily through later Pleistocene time. Modern seismic activity is a manifestation of continuing tectonism. The so-called "mid-Pleistocene" orogeny of the California Coast Ranges was but one phase of a process that has been operating rather continuously since late Miocene time at least.

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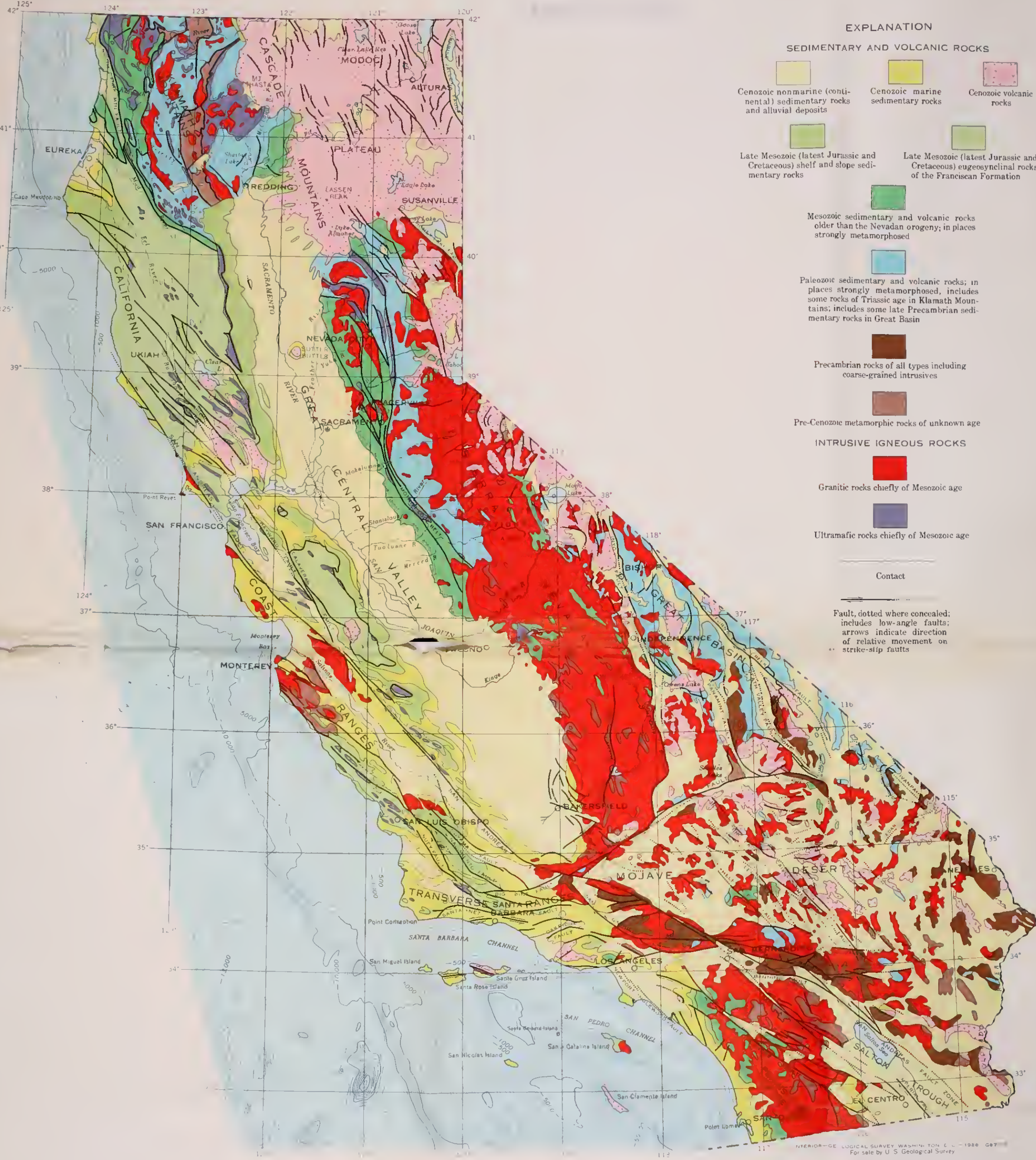
DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits

Cenozoic marine sedimentary rocks

Cenozoic volcanic rocks

Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks

Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation

Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed

Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin

Precambrian rocks of all types including coarse-grained intrusives

Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

Granitic rocks chiefly of Mesozoic age

Ultramafic rocks chiefly of Mesozoic age

Contact

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

For sale by U S Geological Survey

GEOLOGIC MAP OF CALIFORNIA

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

SCALE 1 2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET DATUM IS SEA LEVEL

1966