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THE QUATERNARY OF THE PACIFIC MOUNTAIN SYSTEM IN CALIFORNIA*

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The Quaternary of California is a system of great variety and complexity. Nearly all the climatically controlled phenomena recorded in other parts of the world—glaciation, periglacial phenomena, changes of sea level, fluctuations of pluvial lakes, alluvial-terrace formation, and soil-forming processes—are present in California, which was undergoing during the Quaternary a major tectonic revolution accompanied by volcanism. The close proximity of the various kinds of Quaternary features, and their association with tectonics and volcanism, have given rise to hopes that the different kinds of climatic succession might be correlated more successfully in California than elsewhere. To date these hopes have been only partially realized, although parts of the glacial sequence have been correlated with radiometrically dated volcanic rocks.

Limitations of space and time have made it possible to cover at length Quaternary phenomena in only four provinces: the Sierra Nevada, Great Valley, Coast Ranges, and Klamath Mountains. The important marine Quaternary succession in Southern California is treated only briefly. The pluvial chronology of the desert basins in eastern California will be found in the chapter on the Quaternary Geology of the Great Basin (Morrison, this volume).

Pre-Quaternary Geologic History

California lies mostly in the eugeosynclinal part of the Cordilleran mobile belt. In most of the state, volcanic rocks and clastic sediments accumulated during the Paleozoic and first half of the Mesozoic, but a thick miogeosynclinal succession of carbonate rocks, quartzite, and shale accumulated along its eastern margin. In late Jurassic and early Cretaceous time (140 to 80 million years ago) the rocks of the geosyncline were intensely folded and faulted, partly metamorphosed, and intruded by enormous composite granitic batholiths, which are now exposed over most of the high mountain ranges and probably underlie much of the Great Valley. This granitic and metamorphic terrane (here called Sierran basement) constitutes one of the two major basement types whose structure and mechanical properties influenced late-Cenozoic deformation.

In Jurassic and Cretaceous time, during and after the emplacement of the batholiths, there accumulated on the sea floor immediately west of the deformed belt a great thickness of clastic sedimentary rocks. These rocks can be divided into two belts: (1) an eastern belt of relatively fossiliferous and well-bedded flysch-type sediments, 6,000-10,000 m thick along the east border of the Coast Ranges, which thins eastward and laps onto the Sierran basement; and (2) a western belt of poorly fossiliferous, irregularly bedded arkosic wacke, argillite, radiolarian chert, and greenstone, intruded by alpine-type serpentinite and ultramafic bodies. The western belt, called the Franciscan Formation, is intensely deformed and locally metamorphosed. The Franciscan Formation underlies large segments of the coastal part of California and constitutes the second of the two major basement types, which is here called Franciscan basement. Its base has never been seen (Bailey *et al.*, 1964).

The eastern half of the state has been land continuously since the mid-Cretaceous orogeny, but the western half has at various times been partly or wholly submerged. The early Cenozoic was a time of relative quiescence. Tectonic activity increased in upper Miocene time, when several of the deep basins of Southern California were blocked out (Emery, 1960). Tectonism continued through the Pliocene, resulting in accumulations of thousands of meters of sand, silt, and gravel of marine and continental deposition in narrow basins. Near the end of the Pliocene the sea was expelled to near the present shoreline. Orogenic activity may have reached its climax in the early Quaternary, when many of the lower Pleistocene formations were folded, although the climax was reached in various parts of the state at various times within the upper Cenozoic, and some areas appear to be as tectonically active today as at any time in the past.

A system of long northwest-trending transcurrent faults, possibly dating back to the Cretaceous, has broken the coastal part of California into narrow slices and is still active. The most important fault, the San Andreas, is estimated to have a right-lateral offset of 500 km since Cretaceous time and 280 km since lower Miocene time (Hill and Dibblee, 1953; Curtis *et al.*, 1958); geodetically measured drift of opposite sides of the fault past each other is 5 cm per year at the present time (Whitten, 1949, p. 88).

More detailed accounts of the tectonic history of California are to be found in Reed (1933), Reed and Hollister (1936), Jenkins *et al.* (1943), Jahns (1954), King (1958, 1959), and Bowen (1962). The papers by King are especially recommended for their comprehensive view of the place of California in the tectonic pattern and history of

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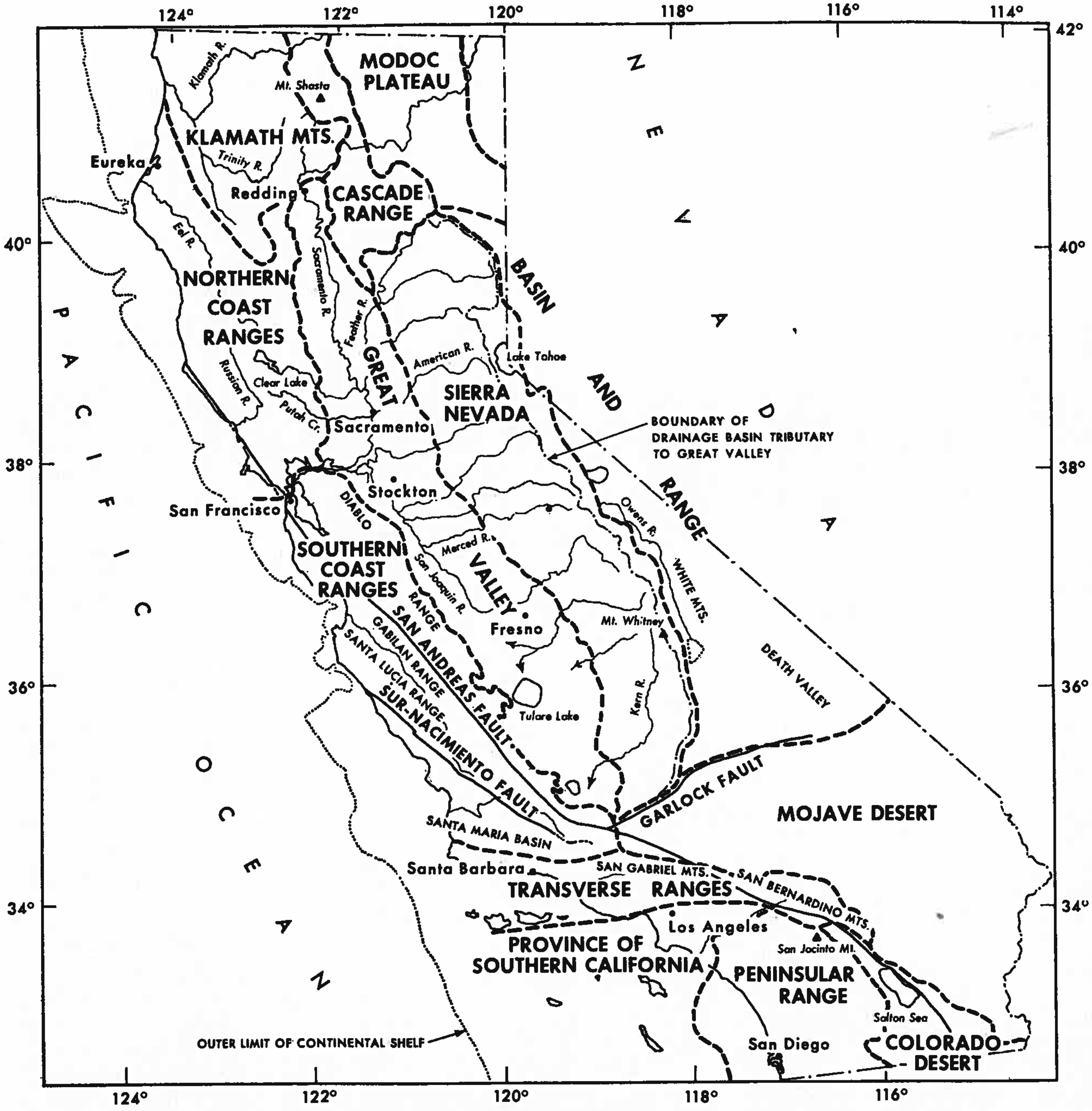

Figure 1. Physiographic provinces of California. Modified from Geomorphic Map of California by Olaf P. Jenkins, *in* Hinds, 1952, Pl. 2.

western North America. A geophysical model for central California is presented by Thompson and Talwani (1964).

Physiographic Divisions

The physiographic divisions of California are shown on Figure 1. They are described in detail by Fenneman (1939) and Hinds (1952). The following brief summary is designed to acquaint the reader with the physical setting of the Quaternary deposits.

BASIN AND RANGE PROVINCE

Along its eastern margin, California includes part of the predominantly arid Basin and Range province. Narrow rugged north-trending ranges 15-18 km wide and 40-150 km long rise 900 to 3,300 m above deeply alluviated valleys 8-25 km wide. White Mountain Peak is 4,350 m above sea level, and Death Valley 90 m below. The major relief features are of fault origin, and the valleys are graben or down-dropped sides of tilted fault blocks. Fresh scarplets cutting alluvium along the range fronts indicate that faulting is still active. Drainage is almost entirely internal, and the few perennial streams that rise in the high mountains (chiefly in the Sierra Nevada west of this province) lose themselves in playas or salt lakes.

The mountains of the northern part of the province are chiefly of volcanic rocks of Pliocene and Pleistocene age, resting on a crystalline, largely granitic basement. South of the latitude of Yosemite, the mountains consist predominantly of folded and faulted miogeosynclinal Paleozoic rocks, locally intruded by granitic plutons. The playas are underlain by thick deposits of salines, including borates; similar evaporates in deformed sedimentary sequences as old as lower or middle Pliocene and possibly older (Dibblee, 1958; Drewes, 1964) indicate aridity and interior drainage well back into the Tertiary.

The southernmost part of the Basin and Range Province in California is divided into two sub-provinces: (1) the Mojave Desert, an area of low northwest-trending ranges, broad pediments, and alluviated basins, underlain chiefly by crystalline rocks; and (2) the Colorado Desert, a low-lying plain, locally below sea level, underlain by deformed Cenozoic sediments and thick alluvial fill.

MODOC PLATEAU AND CASCADE RANGE

The Modoc Plateau is an irregular basaltic plateau 1,200-1,500 m high, surmounted by numerous volcanoes that rise 300-600 m higher. It is segmented into fault blocks by numerous northwest-trending faults, whose fresh scarps are 100-500 m high. The southernmost 250 km of the Cascade Range is in California and is essentially the slightly upturned western edge of the Modoc Plateau, dominated by two great Quaternary volcanoes, Mt. Shasta, 4,300 m, on the north, which bears glaciers, and Lassen Peak, 3,200 m, on the south, which was active in 1917.

SIERRA NEVADA

The Sierra Nevada is a great westward-tilted fault block. Its eastern slope is an abrupt mountain wall rising 750 to 3,100 m at an average slope of 15%, and locally 35%, to reach crestline altitudes of 2,500-4,400 m. For long distances the eastern slope is a rugged, deeply dissected fault scarp, but in places it is a complex of faults *en echelon*, ramp structures, and monoclines. The gentle western slope descends from the crest to altitudes of 100-200 m at its foot in distances of 80 to 100 km. Streams on the west slope have cut narrow gorges 600-2,000 m deep into an upland surface that slopes gently westward in the north part and descends in a series of steps with fronts 50-750 m high in the south part.

Bedrock includes Paleozoic and Mesozoic metamorphic rocks intruded by a great complex of granitic rocks. The great Sierra Nevada batholith, a complex of many plutons, lies east of 120°00′; to the west, metamorphic rocks predominate. A superjacent cover of early Cenozoic auriferous gravels, Miocene rhyolitic ignimbrite, and Pliocene andesitic mudflows caps the upland surface of the northern Sierra Nevada. Scattered remnants of Cenozoic basalt flows, many of them Quaternary, are found in the southern part of the range. A region 55 km wide along the crest of the range was intensely glaciated.

KLAMATH MOUNTAINS

The Klamath Mountains are a very rugged mountain region in northwestern California and southwestern Oregon. Clusters of high peaks 1,800-2,700 m in altitude rise above a general level of accordant summits, which are at 900 m on the west and 1,500-1,800 m on the east. Narrow canyon floors are less than 300-750 m above sea level even near the center of the range, giving the mountains a local relief of 900-1,500 m.

The Klamath Mountains are underlain by a central belt of ancient schist, flanked on the east by highly deformed Paleozoic sedimentary and volcanic rocks and on the west by metamorphosed Jurassic(?) rocks. Structural trends are northwest in the southern part, north at the Oregon border, and northeast in Oregon, where this terrane passes beneath the volcanics of the Cascade Mountains to reappear as an east-trending belt in northeast Oregon. Intrusive rocks include enormous ultramafic bodies and small batholiths and stocks of granitic rocks (Irwin, 1960).

NORTHERN COAST RANGES

The northern Coast Ranges are an almost continuously mountainous highland area whose summit altitudes range from 800 m in the west and south to 1,800-2,200 m in the north and east. On their east side they drop abruptly to a belt of low foothills bordering the Sacramento Valley. Bedrock is chiefly the Franciscan Formation. The eastern foothills have a valley-and-ridge topography developed on a steeply dipping homoclinal sequence of Jurassic and Cretaceous sandstone and shale. Downfaulted late-Cenozoic sediments underlie isolated basins within the mountains; they flank the southern margin of the mountains along San Francisco Bay. A large field of volcanics of Pliocene and Pleistocene age extends due south across the southern part of the range.

SOUTHERN COAST RANGES

Just north of San Francisco Bay, the northern Coast Ranges split into four or five parallel ranges separated by structural valleys. The Coast Ranges southward from San Francisco Bay are two or three parallel mountain ranges 15-50 km wide separated by structural depressions 1-15 km wide. The ranges trend slightly obliquely to the province as a whole, so that the valleys open northwestward to the sea or southeastward to the Great Valley. Except at the extreme southeast end, where several mountains reach altitudes of 2,400-2,700 m, the ranges are less than 2,000 m high, and range-crests are commonly 750-1,400 m high. Local relief is 300-600 m, but some fault scarps are 900-1,200 m high. The valleys are commonly less than 250 m above sea level. The border with the Great Valley is generally abrupt; the Santa Lucia Range has a particularly bold coastline: mountains 1,000-1,500 m high lie within 4 or 5 km of the coast.

The southern Coast Ranges are extremely complex geologically. The basement consists of granitic and metamorphic rocks of the Sierran type under a belt 40-65 km wide extending diagonally through the center of the province. This belt is flanked on both sides by basement of the Franciscan type. The San Andreas Fault bounds the Sierran terrane on the northeast, and the Sur-Naciemento zone forms its southwestern boundary. These major structural blocks are broken into many minor blocks by faults branching from the San Andreas and Sur-Naciemento Faults; the history of each block is different from that of its neighbors. Unconformities are common, with sediments alternately shed from one block to another. The major faults are probably transcurrent faults.

The northeastern part of the central granitic block (the Gabilan Range) has behaved as a single rigid structural mass, while the southwestern (Santa Lucia Range) and northwestern (Santa Cruz Range) parts have been complexly deformed, both by overthrusting and by tight folds, some with granitic cores.

The areas of Franciscan basement have been deformed by folding, and great masses of serpentine have been forced diapir-fashion through the Franciscan and upper Cretaceous sediments.

Much of the deformation of the southern Coast Ranges took place in Quaternary time, and deformed Pleistocene continental and marine sedimentary rocks are widely distributed.

GREAT VALLEY

The Great Valley is a flat alluvial plain mostly less than 300 m above sea level. It is drained by two axial streams, the south-flowing Sacramento in the north half and the northwest-flowing San Joaquin in the south half; their waters mingle in a network of channels in the delta region and enter Suisun Bay, an arm of San Francisco Bay that penetrates to the Great Valley. The connection with the Pacific Ocean is by a series of narrow straits that are the drowned canyons of a Pleistocene river. The climate of the Great Valley is semiarid and under natural conditions it was a treeless, grass-covered plain. The southern fifth of its length normally does not drain to the ocean.

TRANSVERSE RANGES

The dominantly northwesterly trends to topography and structure are abruptly broken between latitude 34° and 35° N by a narrow east-trending belt of ranges, the Transverse Ranges, whose seaward extension is apparently the Murray Fracture Zone. The western half consists of two or three ranges, 10-15 km wide and 600-1,500 m in altitude. Intervening valleys are below sea level on the west (Santa Barbara Channel) and 150-450 m high on the east. The narrow northern ranges—Santa Ynez and Topatopa Mountains—are a steep to overturned sequence of Eocene and Oligocene sandstone, shale, and conglomerate several thousands of meters thick, bounded on the north by a fault; the southern ranges—the Channel Islands and the Santa Monica Mountains—have a core of granitic rocks and slates (of Sierran basement) overlain by folded and faulted Miocene sediments and volcanics. The central trough (the Ventura Basin) has 4,000-4,500 m of marine Pliocene rocks and 1,200-1,500 m of marine Pleistocene rocks—possibly the thickest marine Pleistocene section in the world.

The eastern half of the Transverse Ranges includes two extremely rugged compact ranges, the San Gabriel and San Bernardino Mountains, each about 100 km long and 35-40 km wide, and reaching altitudes of 3,000 and 3,400 m respectively. These ranges are chiefly intrusive rocks and ancient schists, and Precambrian anorthosite is present in the San Gabriel Mountains. The ranges are horsts bounded by steep reverse faults, and the San Andreas Fault passes between them.

PENINSULAR RANGE

The Peninsular Range, south of the Transverse Ranges, is remarkably like the Sierra Nevada. It is a tilted fault block whose bedrock is a complex mid-Cretaceous granitic batholith intruding Mesozoic and Paleozoic volcanic and sedimentary rocks. Thin patches of little-deformed late-Cretaceous and early-Tertiary sedimentary rocks mantle its gentle western slope. The range extends most of the length of the peninsula of Baja California. It rises in broad, low, irregular steps from the Pacific Ocean to crest-line altitudes of 1,700-2,000 m about 55-70 km east of the coast, where it drops abruptly in a series of great desert escarpments 900-1,200 m high to the Colorado Desert.

The northern and northeastern end of the Peninsular Range is sliced diagonally by many northwest-trending strike-slip faults of the San Andreas system. Mt. San Jacinto, in the northeast corner of the province, has been uplifted a maximum height of 3,300 m, and its east face is a dissected scarp over 3,000 m high.

PROVINCE OF SOUTHERN CALIFORNIA

The northwest end of the Peninsular Range is depressed to a deep basin that has been the site of accumulation of marine and continental sediments since early-Miocene time. This triangular lowland is divided into two valleys by a transverse range of hills of folded Miocene and Pliocene sediments. The eastern valley is 150-500 m above sea level and is floored with coarse alluvium from the San Gabriel and San Bernardino Mountains. The western lowland, the Los Angeles Basin, is less than 150 m above sea level.

To the west, beneath the Pacific Ocean, is a region about 125 km wide that contains northwest-trending banks and islands separating basins 1,300-2,000 m deep. This submerged basin-and-range topography was apparently formed in Miocene time and has been slowly filling with sediment ever since—the Los Angeles Basin is merely the basin closest to shore that filled first. The islands exposed Eocene and Miocene sedimentary and volcanic rocks and a Franciscan basement.

Because this submerged region is more closely related to the continent than to the deep sea floor, above which it rises about 3,000 m, it is grouped with the Los Angeles basins and the valley to the east as the Southern California Province.

The Non-Glacial Quaternary of the Sierra Nevada

INTRODUCTION

The study of the Quaternary of the Sierra Nevada involves three problems: (1) the amount of deformation and erosion in Quaternary time, (2) the extent of Quaternary volcanism, and (3) the number and extent of glaciations. The volcanic rocks have recently been dated by the potassium-argon method (Dalrymple, 1963, 1964a, 1964b; Evernden and Curtis, in press) and assigned to geomagnetic polarity epochs (Cox *et al.*, this volume). These dates have not only illuminated the second problem, but the first and third as well. The volcanic rocks are therefore discussed first.

The potassium-argon dates on the volcanic rocks confirm some views on the uplift and erosion of the Sierra Nevada and contradict other views. Taken by themselves, the dates might reasonably be questioned. However, the dated rocks fall into well-defined magnetic-polarity groups. The paleomagnetic data provide an independent test of the validity of the dates.

VOLCANIC ROCKS

Quaternary volcanic rocks are common on the east side of the Sierra Nevada and in the valleys immediately east of its eastern scarp. Scattered flows constitute a diffuse volcanic field extending from Truckee on the west to Virginia City on the east, lying just north of Lake Tahoe (Birkeland, 1963; Thompson and White, 1964). These flows, assigned to the Lousetown Formation, range in age in the Truckee area from 1.2 to 2.3 million years (Birkeland, 1964; Dalrymple, 1964a). They were erupted after the major topographic features had been blocked out by faulting and warping and before deposition of any of the glacial deposits to which they can be directly related. The Carson Range east of Lake Tahoe was arched in part since the earliest of these flows was erupted, and the basin of Lake Tahoe may have originated by downwarping of a segment of a graben during Lousetown time. The Sierra Nevada, however, appears to have had its present elevation above Martis Valley (in which Truckee lies) before the flows were extruded. Andesitic mudflows mantling the northern Sierra Nevada and making up much of the Carson Range, assigned to the Mehrten and **Kates** Peak formations (Curtis, 1954; Hudson, 1955; Thompson and White, 1960), are offset along the range fronts (through warping or faulting) by amounts comparable to the range-front scarps. Their age of 7.4 million years (Dalrymple, 1964a) establishes the major part of this deformation as post-middle Pliocene.

The region from Mono Lake on the north to Independence on the south has experienced major Quaternary volcanic activity that continued to recent times. The volcanic rocks are described by Gilbert (1938, 1941), Putnam (1949, 1960, 1962), Rinehart and Ross (1957, 1964), Bateman (1956, 1962, and in press), Knopf (1918), and Moore (1963).

Basalt flows from 2.6 to 3.2 million years old rest on surfaces of moderate relief and are now tilted and offset by faults with many meters to possibly 1,000 meters displacement (Dalrymple, 1964a; Putnam, 1960, 1962; Gilbert, 1941). A flow 2.6 million years old underlies the McGee till on McGee Mountain, the oldest till recognized in the Sierra Nevada (Blackwelder, 1931). Flows about 3 million years old form the crest of the Sierra at the head of the Middle Fork of the San Joaquin River, where they appear to fill valleys that once extended across the range from the Mono Basin into the San Joaquin drainage.

The Bishop Tuff, a rhyolitic ignimbrite that erupted from several sources within a short interval, totals 145 km^3 in volume and underlies a large area east of the Sierra Nevada between Mono Lake and Bishop (Gilbert, 1938). It is about 700,000 years old (G. B. Dalrymple, oral communication, 1964; G. H. Curtis, oral communication, 1964; see also Cox *et al.*, this volume) and rests on the Sherwin Till, the second oldest of the glacial deposits recognized by Blackwelder (1931; see Putnam, 1960). The Bishop Tuff has been considerably warped and faulted since its extrusion, and the present ignimbrite sheet, 120-150 m thick, ranges in altitude from 1,100 to 2,500 m in a distance of 35 km; much of this relief is probably structural. It is confined to the valley between the Sierra Nevada and the White Mountains, and it appears to have been erupted when the range-front faults had the greater part, if not most, of their displacement. Thus it establishes that much of the faulting on the east side of the Sierra Nevada had occurred by 700,000 years ago, but that some of it was later.

Mammoth Mountain is a large quartz-latite volcano on the crest of the Sierra Nevada near the head of the Middle Fork of the San Joaquin; it is in part 370,000 years old (Dalrymple, 1964a).

Numerous basaltic cinder cones and flows lie along the base of the Sierran escarpment between Big Pine and Independence (Bateman, 1962; Moore, 1963). The flows are interbedded with outwash gravels and appear to be associated with outwash of Tahoe age. A flow in Sawmill Canyon rests on till of Sherwin(?) age and underlies Tahoe till; it has an age of 60,000-90,000 years (Dalrymple, 1964b), indicating that the Tahoe Glaciation correlates with the early Wisconsin of the mid-Continental United States.

The youngest volcanoes of the Sierra Nevada are the Mono and Inyo Craters, a line of rhyolitic-tuff rings and plug domes extending from Mono Lake to Mammoth Mountain. Two K-Ar dates on the Mono Craters (Evernden and Curtis, in press) are 56,000 years on one of the oldest sanadine-rich plugs and 5,000 years on a plug dome that erupted after the last high level of Mono Lake. More recent pumiceous ash falls mantle neoglacial moraines. Radiocarbon-dated charred wood from beneath the youngest pumice deposit from the Inyo Craters is 1,440 ± 150 years old (W-727).

Remnants of basaltic flows are widely distributed on the west side of the Sierra Nevada in the basins of the San Joaquin, Kings, and Kern Rivers. Most of these range in age from 2.9 to 3.8 million years (Dalrymple, 1962, 1964a). Several flows descend into the inner canyons of these rivers, and one, 3.5 million years old, descends to within a few hundred feet of the present canyon floor of the Kern River (Dalrymple, 1963).

A volcanic field of well-preserved cones and flows lies in upland valleys on the plateau between the Kern River and its South Fork (Webb, 1950). One of these flows descends nearly to the floor of the Kern River Canyon; several of the flows are mantled by patches of gravel thought to be glacial outwash.

DEFORMATION AND EROSION

At some time within the Cenozoic the Sierra Nevada was tilted westward, and its crest was uplifted a few thousand meters. In response to the tilting, the streams on its western slope carved deep canyons in a surface of moderate to low relief—a surface that in the northern part of the range was the constructional surface on Pliocene andesitic mudflows and in the southern part of the range was eroded on granitic and metamorphic rocks. The region east of the Sierra Nevada was depressed 1,000-3,000 m relative to the mountain crest along a series of faults and monoclinal

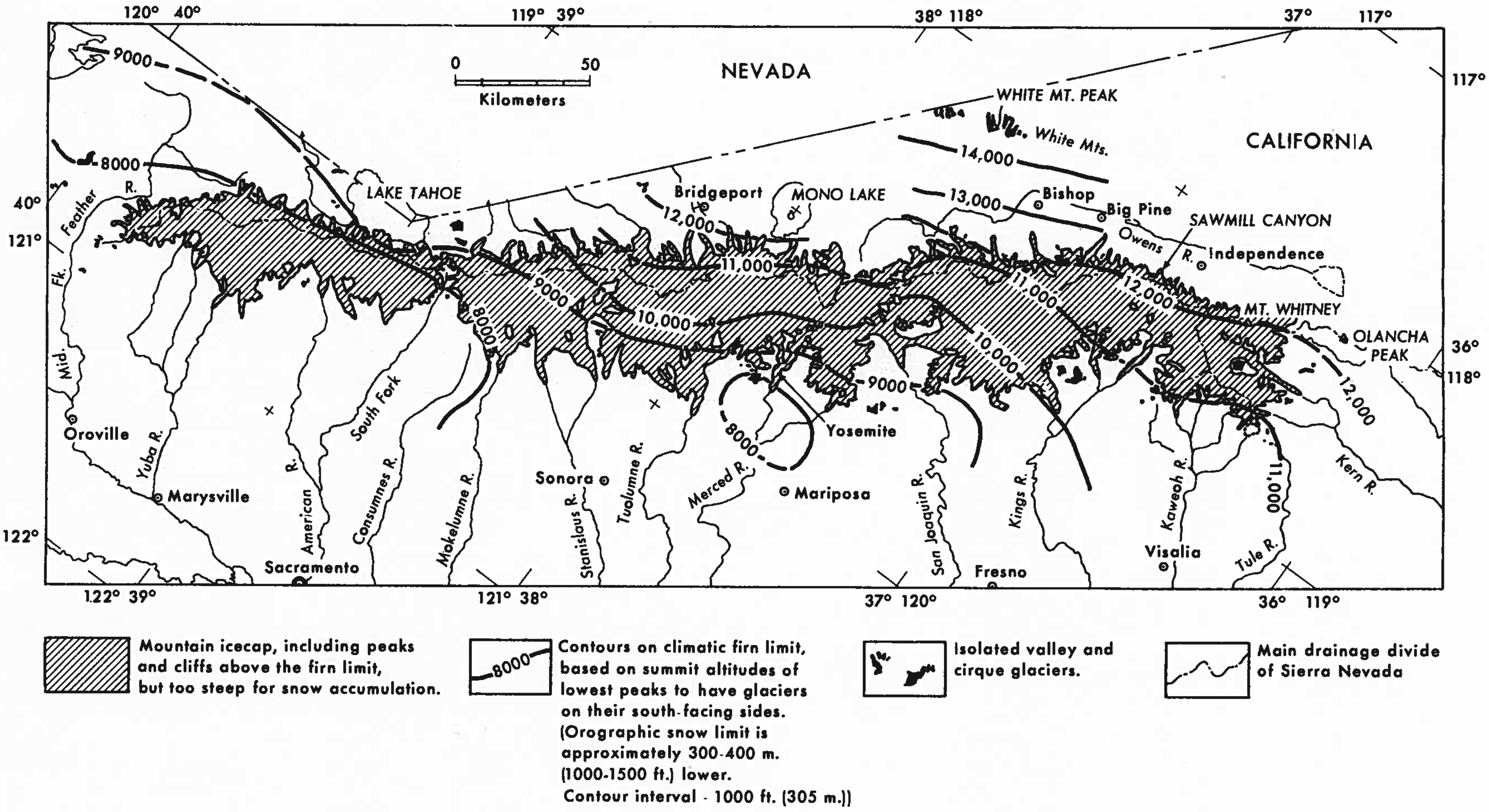

Figure 2. Wisconsin(?) glaciation and climatic firn limit in the Sierra Nevada and White Mountains. Ice limits in Truckee drainage from Birkeland (1964); in Markleeville area from Curtis (1951); on east side of Sierra Nevada between Mono Lake and Independence from Putnam (1949, 1950), Rinehart and Ross (1957, 1964), Birman (1964), Bateman (1956), Moore (1964); in Tuolumne and Merced drainages from Matthes (1930); in San Joaquin drainage from Matthes (1960) and Birman (1964). Remainder of area from study of 1:62,500 topographic maps published by the U.S. Geological Survey, supplemented in a few places by field reconnaissance and by study of distribution of morainal deposits shown on Truckee, Colfax, Pyramid Peak, and Big Trees Folios (Lindgren, 1896, 1897, 1900; Turner and Ransome, 1898).

warps. The uplift of the Sierra Nevada and the faulting along its eastern margin were not necessarily contemporaneous; potassium-argon dating of basalt flows from opposite sides of the range suggests that much of the faulting on the east side occurred after much of the tilting on the west side, as had been suspected by Matthes (1950).

Opinions as to the amount and time of uplift vary widely, as do estimates of the amount of erosion between successive phases of deformation. Lindgren (1911), Matthes (1930, 1960), and Hudson (1955, 1960) estimated uplift and tilting from restored profiles of presumably graded streams of early-Tertiary age. Lindgren and Matthes concluded that the range was tilted more or less as a block, with tilting amounting to about 13-17 m/km, and that uplift along the range crest amounted to 1,300-2,700 m. They assigned the deformation to late-Miocene and Pliocene time. Hudson concluded that the uplift since early-Tertiary time was less than 600 m in the north and less than 1,200 m near Yosemite, and that it took place after the middle Pliocene. His method of calculation led him to conclude that the range had not been tilted as a block but had deformed internally in a fairly complex manner. Recently Christensen (in press b) has evaluated the probable limits of slopes of the original graded streams, and he concluded that the uplift probably lies between 1,200 and 1,500 m in the north and 1,800 and 2,100 m in the south.

Axelrod (1957, 1962; Axelrod and Ting, 1961) has estimated the uplift of the Sierra Nevada on the basis of the climatic implications of paleofloras. In his earlier paper he estimated the uplift at the crest to be between 1,500 and 1,900 m in the Lake Tahoe region; in his later papers he argues for 1,500-2,700 m of uplift, all largely within the Pleistocene.

Matthes (1930, 1960) recognized in the central Sierra Nevada four stages of erosion: an ancient, presumably Eocene surface, almost completely destroyed; the Broad Valley stage, incised 260-500 m into the Eocene surface, and assigned to the Miocene; the Mountain Valley stage, about 180 m below the Broad Valley stage, and assigned to the Pliocene; and a stage of canyon cutting about 450 m deeper, which he placed in the early Pleistocene. Broad surfaces recognized by Lawson (1904), Knopf (1918), and Matthes (1937) in the Sequoia region are the Boreal Plateau, which is correlated with the "Eocene" surface farther north, and the Chagoopa surface, which is correlated with the Broad Valley stage. Axelrod and Ting (1961), challenging Matthes' age assignments, assign the Boreal surface to the late Pliocene and the Chagoopa surface to the early Pleistocene, with the bulk of the uplift of the Sierra Nevada occurring in mid-Pleistocene time. The evidence for this age assignment is the presence of pollen floras of strikingly modern aspect in lacustrine sediments on the remnants of the Boreal and Chagoopa surfaces.

Basalt resting on Matthes' (1960) Mountain Valley (Pliocene) valley floor of the San Joaquin River has yielded a K-Ar date of 9.5 million years (Dalrymple, 1963), which confirms Matthes' age assignment. Several flows ranging in age from 2.9 to 3.6 million years descend into canyons cut into this surface, and the 3.5-million-year flow on the Kern River shows that canyon-cutting was nearly complete by the beginning of Pleistocene time. The data of these basalt flows are not in contradiction to the paleobotanic evidence because the pollen-bearing sediments give only a minimum age for the surfaces on which they rest.

The summit flats and tributary nickpoints that were used by Matthes and others as evidence for stages of uplift and downcutting may have another origin. Wahrhaftig (1962 and in press) points out that in the granitic terrane the summit flats and valley-side benches generally do not slope westward as they should if they are remnants of westward-tilted surfaces. Furthermore, the Chagoopa surface is present only at the headwaters of the Kern River; it narrows downstream and disappears in the rugged Kern Canyon. In his view the summit flats and graded reaches between nickpoints are graded to fortuitous local base levels established by massive granitic outcrops, which are more resistant to erosion than the buried granite beneath the benches because they are dry most of the time and weather extremely slowly (*cf.* Büdel, 1957).

GLACIAL GEOLOGY OF THE SIERRA NEVADA

INTRODUCTION

The Sierra Nevada at the present time has only a few cirque glaciers on the north sides of peaks ranging in altitude from 3,400 m at 38°15′ N to 4,300 m at 37°00′ N. Climatic snow line (Flint, 1957, p. 47) is at 4,500 altitude at latitude 37° N. The climate of the Sierra Nevada, as of the rest of California, is markedly seasonal, with most of the precipitation in winter. Climate is controlled more by topography than by latitude (Dale, 1959, p. 1), and isothermal and isohyetal lines trend northwesterly, parallel to contours. The lapse rate is approximately 6° C/1,000 m (Miller, 1955, p. 14, 70). Winds throughout much of California are westerly to northwesterly, and the maritime climate along the coast gives way to more continental conditions inland.

Precipitation in the Sierra Nevada ranges from 50 to 180 cm per year, and is greater on the western slope than on the rain-shadowed eastern slope. Snowfall may amount to 11.5 m per season at some localities; maximum snowfall in the middle Sierra Nevada is at altitudes of 2,300 to 2,600 m. Snow remains for significant periods only at altitudes greater than 1,300 m, and the season's snow, which begins to fall in October, has usually disappeared except for patches at the highest altitudes by the end of July (Dale, 1959).

In the late Pleistocene a fairly continuous complex of glaciers formed along the crest of the range, with ice tongues descending both slopes. The limits of the Tahoe glaciers are best known (Fig. 2). The Tahoe and Tioga glaciers, and perhaps some of the earlier glaciers, were closely controlled by present drainage patterns and by the general topography of the range, which had already been established. Snowline was probably about 750 m lower during the glacial maxima than now. Ice was most abundant in the southern and central Sierra, between latitudes of 37° and 38° N. To the north, the lower elevation of the range resulted in smaller volume of ice; to the south, the higher temperatures kept the volume small. Because the range is asymmetrical, the larger glaciers were only 16 km long on the eastern slope and as much as 100 km long on the western slope. Ice was not a continuous cap, as the high crest of the range and many ridges and peaks were bare or at most had thin carapaces. In middle reaches of the major stream systems, large ice fields were formed where glaciers rose high enough to override divides between tributaries. Such reservoir-like masses existed in middle latitudes and middle altitudes (1,800-2,500 m). Above 2,500 m they were fed by individual glaciers; below 1,800 m they fed individual glaciers that extended several miles down main canyons. The largest of these masses were in the San Joaquin, Merced, and Tuolumne River valleys, and each had about 500 km^2 of surface area.

The cirques at 3,200 m on Olancha Peak (latitude 36°15′ N) are the southernmost evidence of glaciation in the Sierra (Knopf, 1918, p. 100), and the Kern River glacier reached down to 2,000 m at latitude 36°20′ (Lawson, 1904, p. 345).

In the central Sierra Nevada, main glaciers descended to altitudes of 1,300 to 2,200 m on the eastern slope (Knopf, 1918, p. 93; Blackwelder, 1931, p. 881; Putnam, 1960, p. 243; 1950, p. 116), and 600-1,200 m on the western slope (Matthes, 1930, p. 55; Birman, 1954, p. 42; 1964, p. 33). The difference is generally attributed to more abundant precipitation on the western slope.

The crest of the Sierra Nevada descends northward and is only 2,200-2,600 m high north of Lake Tahoe. Glaciers are therefore smaller to the north, and there were no great ice fields comparable to the Tuolumne ice mass from latitude 38°30′ to the north end of the range. Most glaciers in this segment did not exceed 32 km in length, and most remained above 1,500 m in altitude (Lindgren, 1896, 1900; Turner and Ransome, 1898). North of Lake Tahoe, the ice was most extensive in Truckee Valley and Bear Valley east and west of Donner Pass (Lindgren, 1907; Birkeland, 1964). Glaciers 5-8 km long formed on uplands at 2,500 m and flowed northeasterly down to 1,500 m at the headwaters of the Middle Fork of the Feather River at latitude 39°45′ N (Averill, 1937, p. 87, Pl. II; Turner, 1897). These were the northernmost large early Wisconsin glaciers in the Sierra Nevada. About 55 km farther northwest are a few small cirques with floors at 1,800 m altitude from which glaciers a few kilometers long descended to 1,600 m altitude (Turner, 1898). The northernmost evidence of Tahoe Glaciation is about 8 km north of latitude 40°, west and south of Indian Valley (McVath, 1959-1960).

HISTORY OF INVESTIGATION

Glaciation was recognized as early as 1863 by J. D. Whitney, California State Geologist, who, in a letter dated July 10, described ice polish and moraines in the Tuolumne Valley, indicating a glacier 300 m thick. In 1865, he credited Clarence King and J. T. Gardiner with recognizing abundant evidence for the existence of glacial ice in Yosemite Valley.

It was John Muir, however, who by acute observation and critical reasoning developed by 1870 an essentially modern understanding of the geomorphology of the Sierra Nevada (Colby, 1950, p. xv). In vivid writing (1872, 1874, 1880), which remains fresh and vigorous today, he emphasized the importance of glacial erosion in the Sierra Nevada. Believing that ice was the chief agent of erosion in Yosemite and elsewhere, he did much to direct attention to the Sierra Nevada and to the need for preservation of its wilderness. Le Conte (1873, p. 325) accepted Muir's concept of glaciation in Yosemite Valley and described glaciation at other localities in the Sierra. His was a retreat from Muir's overemphasis on glacial erosion to a concept of mere modification of existing stream valleys.

From studies between 1880 and 1883, I. C. Russell worked out the history of the Lahontan (1885a) and Mono Lake (1889) regions. He described existing glaciers in the High Sierra (1885b) and Mt. Shasta. He realized (1889, p. 326) that the present glaciers on Mt. McClure and Mt. Lyell are not shrunken remnants of the great Pleistocene glaciers but have re-formed after a period of desiccation since the last high-water stand of Lake Lahontan.

Glacial deposits were shown on the Geologic Folios of the U.S. Geological Survey (Lindgren, 1896, 1897, 1900; Turner, 1896, Turner and Ransome, 1898). Turner (1898, 1900) correctly interpreted the role of ice as modifying the stream-eroded topography of the Yosemite.

In 1904, A. C. Lawson made the first study of glaciation in the southern Sierra. He established the southernmost limits of Sierran glaciation and worked out the ice development in the upper Kern and Kaweah basins.

Between 1905 and 1907, W. D. Johnson, who had surveyed topography for Russell, recognized three definitely separable glacial advances, as indicated by two young tills and one much older till in the area between the West Walker River and Mono Lake (Blackwelder, 1931, p. 867). Johnson died before publishing the results of his reconnaissance of the eastern slope of the southern half of the Sierra Nevada.

Modern work in the Sierra began with the studies of François Matthes and Eliot Blackwelder, who worked, respectively, on the western and eastern slopes of the Sierra. Matthes was an ardent naturalist and, like Muir, was an acute and powerful observer with wide experience in recognizing past and present glacial activity. His culminating work was the *Geologic History of Yosemite Valley* (Matthes, 1930). After his Yosemite studies, in which California glacial deposits were mapped in detail for the first time, Matthes turned his attention southward to the San Joaquin and Sequoia–Kings Canyon regions. The San Joaquin studies, made in 1921, 1923, and 1927, have been published posthumously (1960); those of the Sequoia region are in press. These studies have been edited with rare skill by Fritiof Fryxell, who supplemented the observations of Matthes with his own. In all his major works Matthes recognized that Pleistocene glaciation was multiple, used the term Wisconsin, and recognized pre-Wisconsin glaciation. He first proposed the term "Little Ice Age" (1942, p. 214) for the rebirth of glaciers since the disappearance of the Wisconsin ice from the Sierra Nevada.

By 1928 Eliot Blackwelder had already recognized pre-Wisconsin glaciation on the eastern slope, and in 1929 had raised the possibility of still earlier activity. The results of his studies were presented in a series of papers from 1928 to 1932, the most important of which is his 1931 paper, in which he discussed the glacial events on the eastern slope of the Sierra and correlated them with events in the Basin Ranges and Rocky Mountains and with standard Midwestern glacial stratigraphy. He recognized the possibility of five stages (1931, p. 869) as predicted by Antevs in 1925, but his major contributions include the first use of quantitative criteria such as granite-weathering ratios and boulder-frequency counts for distinguishing separate glacial advances in California. In 1930 and 1931 he established the Tioga, Tahoe, and Sherwin glacial stages now used and applied in all modern studies. In 1932 he published the first map showing the distribution of glaciers throughout the Sierra. Blackwelder and Matthes consulted with each other but could not agree on precise correlation across the crest of the Sierra.

Later work in the Sierra Nevada was by Putnam on the eastern slope in Rock Creek (1960, 1960b), June Lake (1949), Mono Lake (1950), and McGee Mountain (1962); Sharp (1963) in the Bridgeport basin north of Mono Lake; Birman (1954, 1964) in the San Joaquin drainage on the west slope and Rock Creek on the east slope; Birkeland (1964) in the Truckee area; Thompson and White on Mt. Rose (1964); McAllister (1936) near Lake Tahoe, and Curtis (1951) near Markleeville. Work is in progress by Birkeland, by Birman in the Sequoia–Kings Canyon area, by Sharp on the east slope, and by R. J. Janda in the Middle Fork drainage of the San Joaquin River.

STRATIGRAPHY

Matthes established a threefold sequence (1930, p. 50-83):

Wisconsin (youngest)
El Portal
Glacier Point (oldest)

The Wisconsin stage was defined to include well-developed lateral moraines and closed or nearly closed recessional-moraine arcs, all of which are well preserved, bouldery, and little weathered. The El Portal stage refers to bulky lateral moraines, generally without closing arcs, recording greater extent of ice, and distinctly more weathered than the Wisconsin moraines. The Glacier Point stage refers to scattered erratic boulders on deeply weathered bedrock above the limits of the lateral moraines of the El Portal stage.

On the eastern slope of the Sierra, Eliot Blackwelder established a fourfold sequence (1931, p. 870):

Tioga (youngest)
Tahoe
Sherwin
McGee (oldest)

The Tioga and Tahoe Glaciations are assumed by most workers to represent late- and early-Wisconsin glacial activity, as they are represented by well-defined, well-preserved lateral moraines and, in the case of the Tioga, by only slightly eroded recessional-moraine arcs. This age assignment is in agreement with the potassium-argon dates reported above. Much of the original topography of the Sherwin deposits has been destroyed. The McGee Glaciation is represented by erratic boulders and weathered till perched on a mountain top high above the younger deposits.

Blackwelder and Matthes disagreed on exact correlation, and Blackwelder concluded (1931, p. 909) that: (1) the Wisconsin stage of Matthes included Tioga and Tahoe; (2) El Portal was equivalent to Sherwin; (3) the Glacier Point stage was not clearly established; and (4) there was no clear evidence for the McGee on the western slope of the range. Blackwelder correlated the Tioga and Tahoe respectively with the Pinedale and Bull Lake Glaciations of the Wind River Mountains, Wyoming, and with late Wisconsin and early Wisconsin (Iowan) of the standard Midwestern section (1931, p. 918). Sherwin and McGee were believed to represent Kansan and Nebraskan glaciations respectively, with the Illinoian not yet discovered in the Sierra. Birman (1957, 1964) and Sharp and Birman (1963) added the name Tenaya for glacial activity between Tioga and Tahoe. Birman (1957, 1964) recognized a threefold sequence, listed from oldest to youngest, Hilgard, Recess Peak, and Matthes, for post-Wisconsin events. Sharp (Sharp and Birman, 1963) introduced the term Mono Basin for a glaciation between Tahoe and Sherwin activity. The glacial sequence is summarized in Table 1.

In the Truckee area north of Lake Tahoe, Birkeland (1964) recognizes the Tioga and Tahoe Glaciations and two older, slightly more extensive glaciations, whose valley-train terraces and moraines have well-developed soils that the terraces of the Tahoe Glaciation lack. These older glaciations he calls the Donner Lake and Hobart (oldest) Glaciations. Both these glaciations are younger—probably much younger—than the Lousetown basalt flows dated at 1.3 million years.

On Mt. Rose northeast of Lake Tahoe, Thompson and White (1964) recognize Tioga and Tahoe tills. Older till they tentatively correlate with the Sherwin Glaciation.

SUMMARY OF GLACIATION

Tioga–Tenaya–Tahoe. This sequence, which is presumed to be Wisconsin, accounts for the most obvious glacial expression in the Sierra Nevada. The presumed Wisconsin age is supported by the 60,000-90,000 year K-Ar date on basalt beneath the Tahoe till in Sawmill Canyon (Dalrymple, 1964b). The probable extent of ice of this sequence is shown on Figures 2 and 3.

The deposits include well-formed and well-preserved stream-truncated lateral moraines, within which are smaller lateral moraines with complete or nearly complete recessional-moraine arcs. The younger Tioga moraines are more bouldery, less weathered, better preserved, and less eroded than the Tahoe. The Tenaya deposits are difficult to recognize without detailed mapping of the Tioga-Tahoe contact. Deposits assigned to the Tenaya have qualitative and semi-quantitative morphological and weathering characteristics intermediate between those of the Tioga and Tahoe and are not easily related to either of the latter.

In the larger canyons of the western slope, the Tahoe lateral moraines are difficult to discern because of extensive forest cover, lack of end moraines, and position of the moraine crests rather high on the valley walls. Their expression is much better in the small tributary canyons, where the Tahoe moraines are well-defined bulky ridges with few boulders on the surfaces. In general, they are the outermost and highest of the deposits that can still be recognized as having original moraine morphology.

On the Merced River, six moderately well preserved moraines at the west end of Yosemite Valley, mapped by Matthes as the Wisconsin terminals, are considered by the junior author to represent the Tenaya Glaciation. The Tioga Glaciation is represented by small but abundant and bouldery moraines on the floor of Little Yosemite Valley above Nevada Falls. At least part of the till mapped by Matthes as El Portal is believed to have been deposited during the Tahoe Glaciation.

In the San Joaquin drainage, the Tahoe glaciers extended down to about 1,100 m altitude in the main canyon. The trunk Tahoe glacier of the San Joaquin River was about 80 km long and 300 to 450 m thick; it is typical of the Tahoe glaciers in the larger canyons on the western slope of the central Sierra Nevada. Tenaya and Tioga deposits in this drainage are abundant down to altitudes of about 2,300 m. One of the best expressed of the Tenaya and Tioga complexes is in the vicinity of Lake Thomas A. Edison Dam on Mono Creek, a tributary of the South Fork of the San Joaquin River. The moraines are small, easily identified, and very bouldery. Most of the Tenaya and Tioga glaciers were about 16 to 32 km long.

The floor of the Kings Canyon contains several rather obscure moraine arcs that are believed at this time to be Tenaya. Tioga ice was confined to the higher parts of the canyons. All three glaciations reached the Lodgepole area of Sequoia National Park in the upper drainage of the Kaweah River. The famous Giant Forest area of Sequoia National Park does not appear to have been glaciated, for it lies just outside the outer limits of Tahoe Glaciation, and in this area there is no evidence of pre-Tahoe glaciation.

Although the Tenaya and Tioga moraines are the most easily discerned on the western slope, it is the Tahoe moraines that are best expressed, especially as seen from a distance of several kilometers, on the eastern slope. Most of the canyons from the vicinity of Lone Pine at least as far north as Lake Tahoe contain well-preserved lateral and

TABLE 1

Description of Glacial Deposits, Sierra Nevada

Glaciation	Types of deposit	Age criteria
Matthes (youngest)	Cliff glacierets, perennial snowfields, rock glaciers; in headwalls of high cirques.	Slopes unstable; boulders free of lichens; interstitial ice; no soil.
Recess Peak	Recessional moraine arcs and short lateral moraines. Scattered boulders on bare bedrock, in cirques and cirque valleys.	Slopes stable, but all boulders very fresh. Lichens on boulders; a little interstitial soil. Glacial polish unusually abundant.
Hilgard	Recessional-moraine arcs and short lateral moraines. Scattered boulders on bare bedrock.	About 70% of moraine boulders are weathered. Polish on weathered materials. Virtually no modification by postglacial erosion; terminal arcs complete.
Tioga	Lateral moraines about 300 m high in larger valleys. End moraines 1.5-5 m high. Thin ground moraines. Scattered erratics on bedrock.	End moraines abundant. Dark inclusions, and aplite and pegmatite dikes protrude only slightly from bedrock or not at all. About 30% of boulders are weathered. Till surfaces very bouldery. Dissection of moraines negligible except by main streams.
Tenaya	Lateral moraines about 300 m high in larger valleys. Rare end moraines 8-15 m high. Ground moraine and glaciofluvial deposits. Scattered erratics on bedrock.	End moraines largely destroyed. Glacial polish still present on aplite and pegmatite dike surfaces and on dense fine-grained lava. Mafic inclusions and aplite and pegmatite dikes protrude slightly or not at all. About 50% of boulders are weathered. Till surfaces moderately bouldery. Moraines dissected by gullies 3-12 m deep.
Tahoe	Lateral moraines 450-600 m high in larger valleys. Ground moraine of gentle relief. Scattered erratics on bedrock.	Glacial polish found only on recently uncovered bedrock. Weathering pits and pans rare and shallow. Rock pedestals are rarely over 2 cm high. Mafic inclusions and aplite and pegmatite dikes protrude as much as 7 cm. About 70% of boulders are weathered. Till surface is not markedly bouldery. Moraines dissected by gullies 3-20 m deep.
Mono Basin	Well-formed lateral-moraine segments truncated by Tahoe moraines in Walker Creek and other canyons of the eastern slope of the Sierra Nevada. Glaciation apparently less extensive than Tahoe glaciation.	Original morphology better preserved than on Sherwin deposits, but only 5% of boulders are unweathered. Truncated by Tahoe glacial deposits. More clearly related to present drainages than Sherwin glacial deposits.
Sherwin	Bulky morainal masses with initial forms largely destroyed and obscured by surface wash. Scattered erratics on bedrock.	Bedrock weathered to 20 cm below surface. Weathering pits and pans as much as 20 cm deep. Rock pedestals as much as 1.5 m high. Mafic inclusions protrude 15-20 cm above surrounding bedrock. 85-100% boulders weathered.
McGee	Erratic boulders with little or no till matrix. Outside and above the deposits of the younger glaciations.	Extensive weathering of boulders and bedrock surfaces, absence of till matrix, and occurrence on high and rather isolated ridge crests, not related to present drainages.

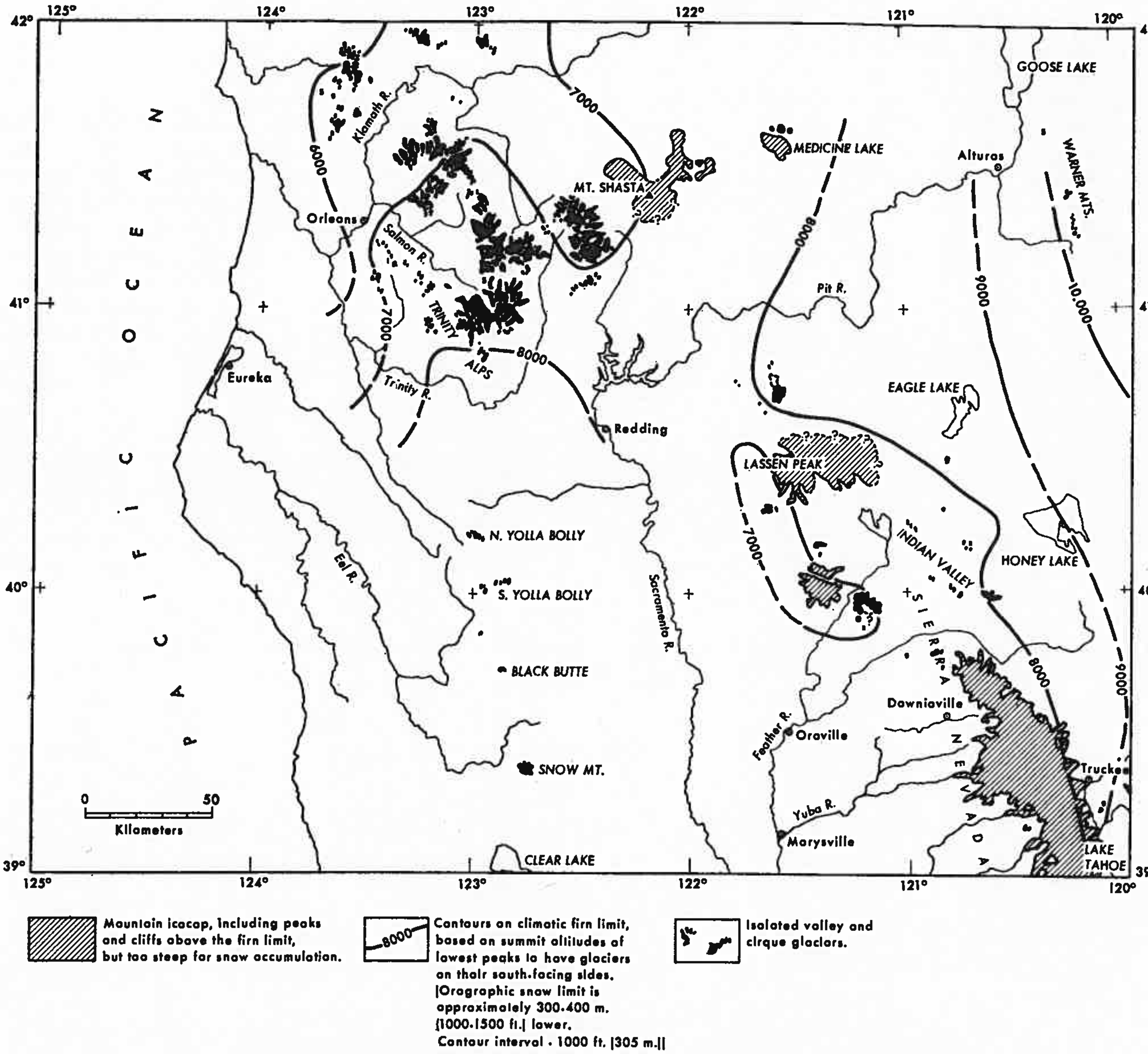

Figure 3. Wisconsin(?) glaciation and climatic firn limit in California north of latitude 39°00′. Ice limits in Truckee area are from Birkeland (1964); in Medicine Lake area from Anderson (1941); Mt. Shasta area from Williams (1949); Trinity Alps in part from Sharp (1960); northern Coast Ranges from Davis (1958). Remainder from study of 1:62,500 topographic maps published by the U.S. Geological Survey, supplemented by study of distribution of morainal deposits shown on Lassen Peak, Bidwell Bar, Downieville, and Colfax Folios (Diller, 1895; Turner, 1897 and 1898; Lindgren, 1900) and "Geologic map of Manzanita Lake Quadrangle" (MacDonald, 1963).

end moraines with associated outwash of the Tioga, Tenaya, and Tahoe Glaciations. Most of the glaciers extended beyond the mouths of the canyons and built spectacular protruding morainal embankments. The general pattern is that of large lateral moraines with truncated ends, within and against the inner sides of which are smaller lateral moraines. The innermost moraines continue across the valley as complete or nearly complete moraine arcs. The outermost and largest of the moraines are Tahoe; the innermost with nearly complete recessional arcs are Tioga. The Tenaya moraines are mostly truncated but are distinctly more bouldery than the Tahoe and less bouldery than the Tenaya. The truncated or partially truncated curving ends of the Tenaya moraines merge upvalley into a rather distinct lateral-moraine crest intermediate between the Tioga and Tahoe crests.

Pre-Tahoe glaciation. The recent work of Sharp (Sharp and Birman, 1963) has identified the Mono Basin Glaciation in the lower part of Bloody Canyon (type locality) south of Mono Lake and in the Bridgeport Basin north of Mono Lake. In the Bloody Canyon locality the Mono Basin Glaciation is expressed by two well-preserved lateral moraines which have been cut off upcanyon by the Tahoe lateral moraines. It is possible that some of the glacial deposits mapped as Sherwin on the western slope may be Mono Basin. Moreover, at the Sherwin type locality in lower Rock Creek on the eastern slope (Blackwelder, 1931, p. 895) some of the fresher till within materials mapped as Sherwin may be of Mono Basin age.

The Sherwin deposits at their type locality on lower Rock Creek on the eastern slope of the Sierra are massive till with little original morphology. The till is hummocky but by no means as bouldery as the younger Tahoe till, and till masses cannot be easily recognized from a distance. In many exposures the boulders are sufficiently weathered to be cut as easily as the enclosing matrix. At the type locality the Sherwin till is overlain by the Bishop Tuff, which has been dated at 700,000 years (see above).

On the western slope, the Sherwin deposits are even more difficult to recognize, because of heavy forest cover. Till is difficult to distinguish from slopewash along the canyon walls and can be identified and mapped only after detailed search for distinctive foreign boulders.

The Sherwin deposits are best known from the central Sierra. They are obscure or absent from the northern and southern ends of the range. The Sherwin Glaciation does not appear to have been much more extensive than the Tahoe Glaciation. Sherwin till has not yet been clearly identified as far south as the Kaweah River. It is not yet known whether there was Sherwin ice in the southern tributaries of the Kings River.

The oldest glacial deposits recognized in California are assigned to the McGee Stage (Blackwelder, 1931, p. 902; Putnam, 1960, 1962). The McGee till consists of extensively weathered granitic materials on metamorphic bedrock and on basalt 2.6 million years old (see above). Boulders on the surface of the till at the type locality are solid, but they have been eroded by sandblasting and weathering, so that mafic inclusions stand in relief. Glacial striae are preserved on their under surfaces immediately below the ground surface. The remnant moraines lie on the tops of divides that could not be reached by glaciers in the present canyons. As Putnam (1960, p. 272) points out, the McGee till at the type locality rests on a broad upland 3,000 m in altitude; he estimates at least 1,200 m of displacement on the eastern fault system of the Sierra Nevada since the McGee Glaciation. No McGee till has yet been recognized on the western slope of the Sierra Nevada.

Post-Tioga glaciation. The Little Ice Age of Matthes (1939, p. 520; 1942, p. 190) appears to be represented in the High Sierra by at least three pulses of glacial activity since the disappearance of the Tioga glaciers. The following comments present the viewpoint of the junior author (Birman, 1954, p. 41; 1964, p. 45) and do not necessarily reflect the opinions of other workers in the Sierra Nevada.

The post-Tioga deposits are restricted to the crestal zone of the Sierra at altitudes above 2,700 m from approximately Mt. Whitney on the south to beyond Sonora Pass on the north. This area has an unusually high frequency of lakes and is characterized by extensively polished bare granitic bedrock, with little cover. All of the post-Tioga glaciations extended from cirques formed by Tioga and earlier ice activity. The oldest of the post-Tioga glaciations is referred to a rock-cut trim-line that is everywhere below and separate from the Tioga rock-cut trimline. It is possible that all of the post-Tioga glaciation is also post-Altithermal.

The oldest deposits referable to this group, assigned to the Hilgard Glaciation, consist of well-preserved moraines, at most a few miles from cirque headwalls. The Hilgard moraines contain a surprisingly high percentage of weathered boulders. The content of weathered boulders is attributed to quick removal and deposition of material weathered in post-Tioga, pre-Hilgard time. The Recess Peak ice advance, the second glaciation of this group, is represented by moraines upvalley from the Hilgard moraines, extensively polished bedrock, and at least 90% fresh boulders in the moraines. The Matthes Glaciation, the youngest, is represented by existing cliff glacierets, protalus ramparts, rock glaciers, and moraines that are still so unstable that no soil has yet accumulated in the interstices between boulders, nor are there any lichens on boulder surfaces.

THE QUATERNARY ALLUVIUM OF THE GREAT VALLEY

HISTORY OF INVESTIGATION

The Great Valley of California is one of the major agricultural and petroleum-producing regions of the United States. As there is no rain during the growing season, agricultural development of its fertile alluvial soils requires large volumes of irrigation water, much of which comes from underground reservoirs in the Quaternary alluvium. Decreasing soil fertility with increasing age of the alluvium results in striking similarities between the pattern of land use and the outcrop distribution of the alluvial formations. Petroleum and natural gas, although not of Quaternary age, accumulated in structural traps involving deformed Quaternary formations. Hence the structure and stratigraphy of the Quaternary alluvium has been investigated by the ground-water geologist, the soil scientist, and the petroleum geologist.

During the first 25 years of this century reconnaissance studies of the ground-water possibilities of the San Joaquin Valley (Mendenhall *et al.* 1914) and the Sacramento Valley (Bryan, 1923) were made; deformed Quaternary sediments along the southwest margin of the San Joaquin Valley were mapped (Arnold and Anderson, 1910; Arnold and Johnson, 1910; Anderson and Pack, 1915); and reconnaissance soil surveys established the major soil series (Holmes, Nelson *et al.*, 1915; Nelson *et al.*, 1921). Gilbert (1914, 1917) at this time conducted his classic studies of the transport of sediment by streams in order to measure the effect of hydraulic mining in the Sierra Nevada on silting of agricultural land in the Great Valley.

Subsequently, detailed studies of the ground-water geology of the Mokelumne and Turlock areas (Piper *et al.*, 1939; Davis and Hall, 1959), of the deformed alluvium along the southwest margin of the valley (Hoots, 1929, Woodring *et al.*, 1932, 1940), and of the Plio-Pleistocene deposits of the Sacramento Valley (Anderson and Russell, 1939) established many of the Quaternary formations now recognized. Toward the end of the 1930's the U.S. Bureau of Reclamation started its investigations connected with the Central Valley Water Project. The continuing work of this agency, although largely unpublished, has greatly influenced the thinking of other geologists working in the Quaternary of the Great Valley.

The present phase of investigation (1940 to the present) is related to the enormous development of surface- and ground-water resources through the Central Valley and California Water Projects, and to modern soil surveys conducted by the U.S. Department of Agriculture in cooperation with the University of California.

STRUCTURE AND GEOMORPHOLOGY

The Great Valley is an elongate basin of deposition that has been accumulating sediments since mid-Cretaceous time. These sediments are nearly flat-lying beneath the valley and wedge out eastward against the crystalline basement of the Sierra Nevada (Fig. 4); along the western margin of the valley they are bent abruptly upward in a steeply dipping homoclinal sequence as much as 12,000 m thick. The Quaternary alluvium is the uppermost 30-1,000 m of these sediments.

Five belts of distinctive geomorphology extend the length of the valley and reflect the origin and history of the alluvial sediments (Fig. 5). Along the east and west margins are two discontinuous belts of rolling hill-land, reaching altitudes of 100-300 m and local relief of 30 m, carved on older generally oxidized alluvium, which has been slightly uplifted.

Valleyward from the dissected uplands are two belts of coalescing alluvial fans. The present constructional surfaces of the alluvial fans on the east side date from the last glaciation, and the rivers that built them now cross them in flat-floored trenches 0.5-1 km wide and as much as 90 m deep. The alluvial fans on the west side are still being aggraded. Perennial streams from the northern Coast Ranges cross the fans in raised courses contained between low, flat natural levees. Abandoned stream courses radiating from the heads of the fans are marked by barely perceptible double ridges called channel ridges (Bryan, 1923, p. 28). Drainage from the southern Coast Ranges is largely ephemeral, and the alluvium has accumulated in large part as mudflow deposits; natural levees are lacking along the poorly defined stream courses. In the past 100 years the heads of many of the fans from the southern Coast Ranges have been trenched (Bull, 1964a).

The axial part of the Great Valley is a belt of riverine lands and flood basins. The axial streams that drain the valley (the Sacramento, lower Feather, and San Joaquin Rivers) flow in meandering or braided channels with natural levees 0.5-6 km wide having crests 1-5 m above the floors of flood basins on either side. These flood basins are areas of flat land 10-15 km wide, with dark gray clayey alkaline soils, formerly covered during spring floods by water held in by the natural levees of the axial streams and their tributaries.

The southern fifth of the valley does not normally drain to the sea. A chain of broad, flat lake basins, formerly covered by a few meters of water in spring and winter, lies along its axis. The water that formerly reached these

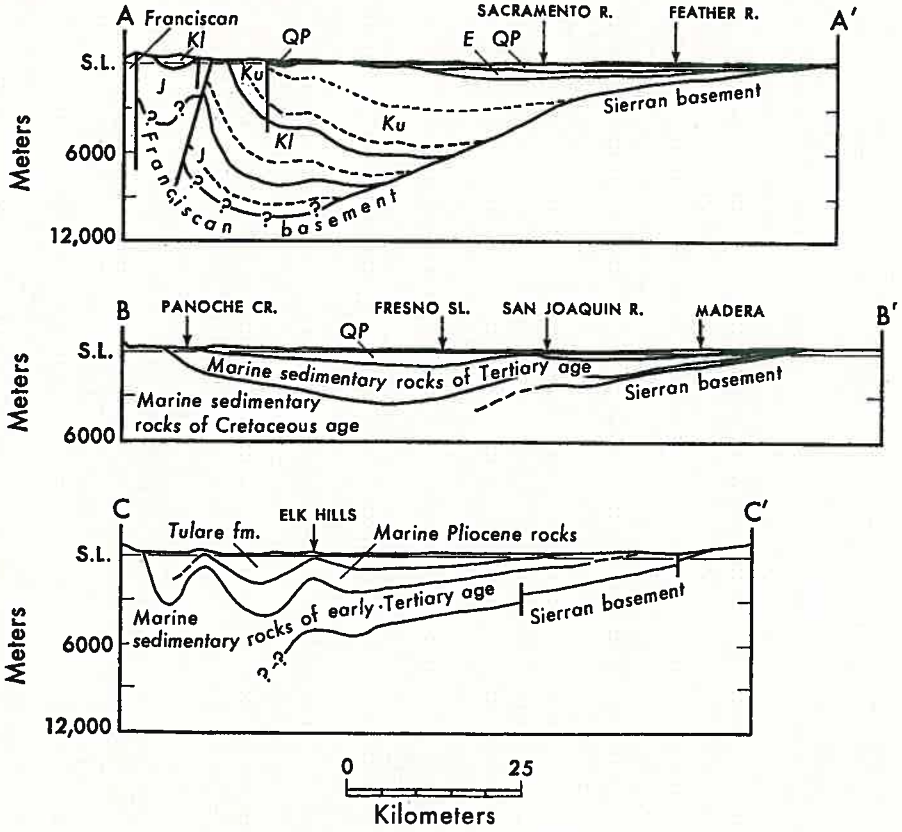

Figure 4. Three cross-sections of the Great Valley of California, showing the thickness of the pre-Quaternary and Quaternary sediments. Section A-A' from Safonov (1962, Fig. 4); Sections B-B' and C-C' from Davis *et al.* (1959, Pl. 2). For location see Figure 5.

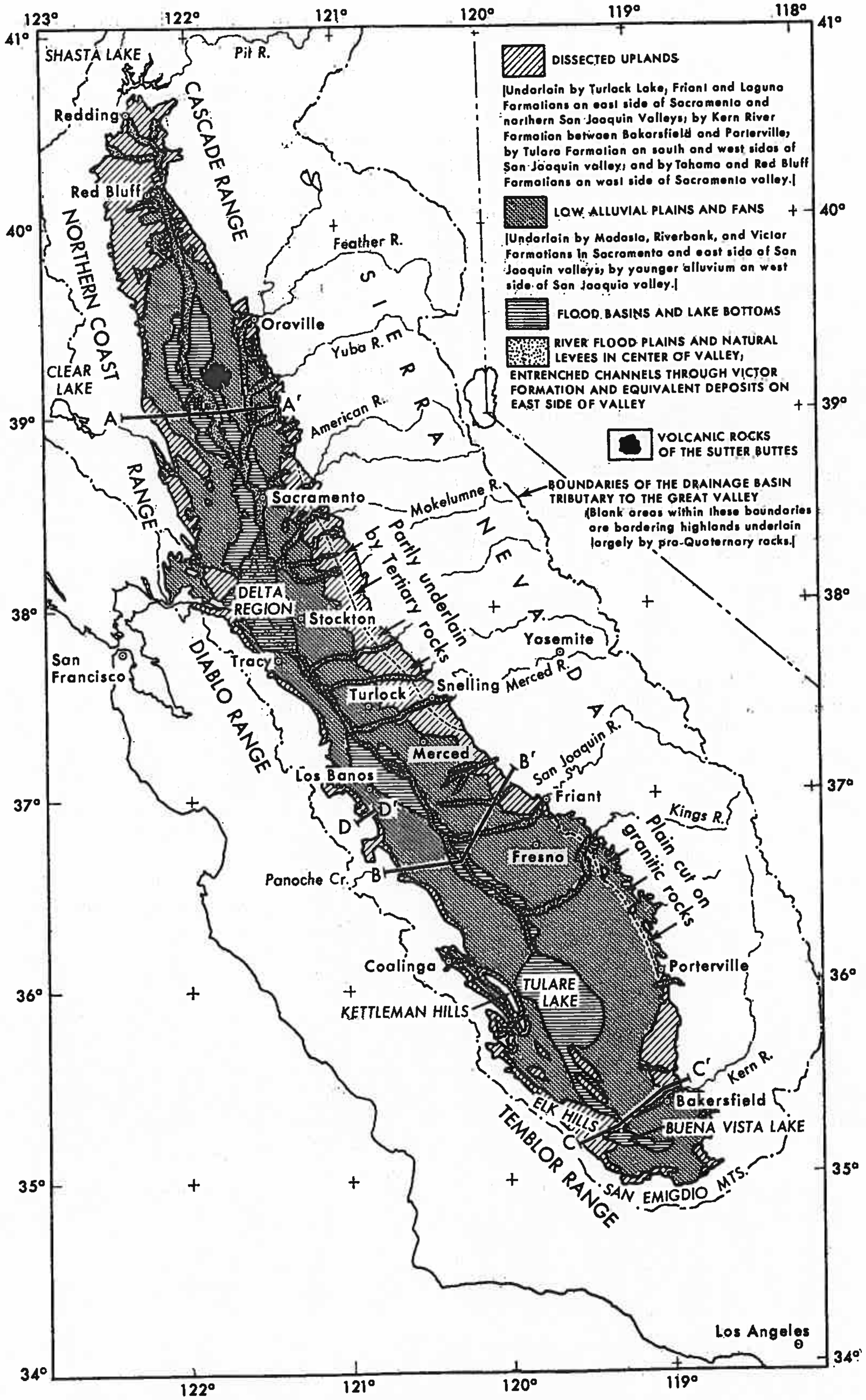

Figure 5. Landforms of the Great Valley of California. Compiled with slight modification from Davis *et al.* (1959, Pl. 1) and Olmsted and Davis (1961, Pl. 1).

basins is now used for irrigation throughout the southern part of the Great Valley.

Beneath the northern half of the Great Valley (the Sacramento Valley) the bulk of the sedimentary fill consists of marine Cretaceous rocks that reach a thickness of 12,000 m in the great homocline along the west side of the valley. Unconformably overlying the Cretaceous rocks, but present only in the southern half of the Sacramento Valley, are less than 2,500 m of lower Tertiary sedimentary rocks (Olmsted and Davis, 1961, p. 37; Lachenbruch, 1962; Safanov, 1962). Continental sediments of late-Pliocene and Pleistocene age, in part volcanic, rest unconformably across the truncated edges of all older rocks (Anderson and Russell, 1939; Olmsted and Davis, 1961). Thus the Sacramento Valley was above sea level during much of Cenozoic time, and it underwent erosion during at least part of the Pliocene.

The Sutter Buttes (formerly called Marysville Buttes), a cluster of fantastically eroded peaks 450-650 m high, rise from the flat center of the Sacramento Valley. The buttes are endogenous andesite domes surrounded partly by an apron of andesitic mudflows about 16 km in diameter, all of early-Pleistocene age (Williams, 1929; Johnson, 1943; Garrison, 1962). Potassium-argon dates on associated rhyolitic intrusions range from 1.5 to 1.9 million years (Evernden *et al.*, 1964).

The southern half of the Great Valley (the San Joaquin Valley) is underlain not only by Cretaceous sedimentary rocks but by a great thickness of Cenozoic rocks as well. The base of the Tertiary succession is 4,300 m below sea level in the central part of the San Joaquin Valley and nearly 5,500 m below sea level at its southern end (Cohee *et al.*, 1961). The Tertiary sequence is predominantly marine on the west side and interfingers eastward beneath the valley with non-marine sands derived from the Sierra Nevada (Church *et al.*, 1957a, b). During the Miocene and early Pliocene an archipelago lay between the San Joaquin Valley and the Pacific Ocean, and the main connection with the sea was at the southwest end of the valley (Hoots *et al.*, 1954). In late-Pliocene or early-Pleistocene time this connection was broken by the rise of the southern Coast Ranges, the sea was excluded, and drainage was redirected northward through the Golden Gate. Since this event, a total of 4,500 m of continental strata has accumulated in the south end of the valley. There is generally no break recognizable in surface or subsurface at the Plio-Pleistocene boundary.

From the vicinity of Coalinga south a series of anticlines plunge southeastward from the Coast Ranges and die out beneath the valley. Movement on these folds involved Pleistocene alluvium, and the surfaces subsequently planed across the folded alluvium have themselves been warped.

A 140-km segment of the east side of the San Joaquin Valley between Friant and Porterville lacks the dissected hill-land on old alluvium. Instead, the flat valley floor extends eastward from the edge of the alluvium for a 4-20 km as a smooth plain developed on weathered granite, and flat-floored embayments extend from this plain into the foothills of the Sierra Nevada, which rise abruptly above this plain in cliffs and bluffs several hundred meters high (Wahrhaftig, in press).

ALLUVIAL FORMATIONS OF THE NORTHEAST SAN JOAQUIN VALLEY

The alluvial sequence of Davis and Hall (1959) in the northeastern San Joaquin Valley near Turlock gives the greatest hope for correlation with the glacial sequence in the Sierra Nevada (Arkley, 1962a, b). Table 2 is a tentative correlation chart of these formations with others in the Great Valley. At the present state of knowledge, a synthesis, except on the most general terms, is premature.

In the Turlock area, the Quaternary formations along the major rivers consist of well-sorted alluvium derived primarily from granitic sources high in the Sierra Nevada. Each formation contains bodies of laminated silt composed of unweathered fragments of feldspar, biotite, hornblende, and quartz, along with bodies of medium to coarse granitic sand, locally pebbly. Each formation was dissected, and a soil developed on the dissected surface, before the deposition of the next formation. Toward the mountains the younger formations are inset into the older formations as terrace deposits lining the trenches cut by the rivers; valleyward, the terraces lap over the trench walls, and the younger formations spread out as coalescing alluvial fans, so that near the axis of the valley the formations lie in normal stratigraphic succession. In the axial part of the valley, deposition may have been continuous, and in this area it is not generally possible to identify the formations in well records. The alluvial formations along the major rivers are thought to be the finest-grained component of outwash from Pleistocene glaciers carried to the valley by melt-water from the Sierra Nevada, because of the predominance in the silts of unweathered particles of hornblende, biotite, and feldspar (R. J. Arkley, oral communication, 1962).

The three alluvial formations recognized by Davis and Hall are the Turlock Lake (oldest), Riverbank, and Modesto (youngest). The Turlock Lake is as much as 240 m thick in the center of the valley and is exposed at the surface throughout much of the dissected upland on the east border of the valley, where local relief is as much as 30 m. It characteristically has either a well-developed soil with a brown acid A-horizon 0.6-0.7 m thick overlying a 1-m-thick reddish-brown clayey B-horizon (Montpelier series) or an eroded soil with a thin A-horizon over an iron-silica hardpan B (Rocklin series). Within the Turlock Lake Formation, wells have encountered a prominent red clayey zone with iron-silica cement, probably a buried soil (Arkley, 1962a). A diatomaceous silty clay correlated with the Corcoran Clay of Frink and Kues (1954—see below) lies in the upper part of the Turlock Lake Formation, according to Arkley.

After the erosion and weathering of the Turlock Lake Formation, the Riverbank Formation was deposited in valleys cut in the older formation. The Riverbank underlies high terraces and slightly dissected alluvial-fan surfaces and has a maximum thickness of 60 m. Well-developed soils with brown or reddish-brown clayey B-horizon and a reddish-brown iron-silica hardpan 0.15-0.4 m thick (the San Joaquin and Snelling series) are developed on the Riverbank Formation.

The youngest formation, the Modesto, underlies the essentially undissected alluvial fans and has a maximum thick-

TABLE 2

Correlation of Formations in the Great Valley

	Sacramento Valley (Olmsted and Davis, 1961)		Mokelumne Area (Piper *et al.*, 1939)	Turlock Area (Davis and Hall, 1959; Arkley, 1961)	Subsurface, San Joaquin Valley (Davis *et al.*, 1959)	Southwest side, San Joaquin Valley (Various authors)
	West side	East side				
Recent	Alluvium and Fan deposits	River deposits	Alluvium	Alluvium	Alluvium and basin deposits	Alluvium
Late Pleistocene	Deeper parts of alluvial fans	Victor Formation	Victor Formation	Modesto Formation		Deformed alluvium
Early Pleistocene	Red Bluff Formation	Arroyo Seco Gravel	Arroyo Seco Gravel	Riverbank Formation Turlock Lake Formation	Alluvial deposits (Tulare Formation) Ash at Friant Corcoran Clay Member	Tulare Formation
Pliocene? and Pleistocene?	Tehama Formation Nomlaki Tuff Member	Laguna Formation Tuscan Formation Nomlaki Tuff Member	Laguna Formation	China Hat Pediment		Lower Amnicola Zone San Joaquin Formation
Pliocene	Neroly equivalents		Mehrten Formation	Mehrten Formation		Etchegoin Formation

? ness of 30 m. The most typical soil developed on it, the Hanford series, shows only a weak humic A-horizon and no textural B-horizon. Recent alluvium mantles the floors of trenches cut into the alluvial-fan surfaces of the Modesto Formation by the rivers from the Sierra Nevada.

The Quaternary alluvial formations rests on andesitic mudflows and volcanic conglomerate of the Mehrten Formation, which ranges in age up to late Pliocene (Hemphillian) (Piper *et al.*, 1939, p. 61; VanderHoof, 1933; Dalrymple, 1963, p. 380). Immediately south of the Merced River near Snelling, gravel consisting largely of resistant metamorphic cobbles from the foothills of the Sierra Nevada caps a high pediment, the China Hat Pediment, cut on the Mehrten Formation, that forms the flat tops of low ridges extending several miles west into the San Joaquin Valley. The gravel is above the highest remnants of the Turlock Lake Formation and slopes more steeply westward; it is therefore older than the alluvial formations (Hudson, 1960; Arkley, 1962a), and it indicates a period of extensive erosion between the deposition of the Mehrten and the Turlock Lake Formations. The gravel has a red strongly acid soil with a 45-90 cm A-horizon of gravelly loam underlain by an iron-silica hardpan 20-60 cm thick (the Redding series); more than 10 m of weathered gravel stained with iron oxide lies beneath the soil.

THE TULARE FORMATION

Along the southwestern and southern border of the San Joaquin Valley a thick series of poorly consolidated sand, silt, clay, and gravel (with a maximum exposed thickness of nearly 1,000 m) conformably overlies the youngest marine Pliocene rocks. This sequence was named the Tulare Formation by Anderson (1905) and has been traced northward from its type section in the Kettleman Hills to Tracy and southward to Tejon Pass (Anderson and Pack, 1915; Arnold and Anderson, 1910; Hoots, 1929; Woodring *et al.*, 1932; Woodring *et al.*, 1940, with summary).

The bottom 20-50 m of the type section is predominantly clay and fine sand, at the top of which is the Lower Amnicola Zone, a fossiliferous and ferruginous sandstone, with beds of water-laid tuff, containing abundant freshwater mollusks and diatoms. Overlying the Lower Amnicola Zone is as much as 900 m of poorly consolidated and poorly sorted lenticular sandstone and conglomerate interbedded with layers of silt and clay, the whole bearing a striking resemblance to the alluvial-fan deposits accumulating along

(45)

the flanks of the Coast Range today. The source of these sediments was in the Coast Ranges west of the Kettleman Hills.

In the Elk Hills farther south, Woodring *et al.* (1932) assigned the uppermost 900 m of the folded sediments to the Tulare Formation. At the south end of the valley, Hoots (1930) mapped 300-1,500 m of gravel, sand, and clay resting conformably on marine Etchegoin (Pliocene), which he assigned to the Tulare. The prominent pebbles in the gravels are of granitic rocks from the core of the San Emigdio Mountains immediately to the south. The Tulare here has been overthrust by Miocene rocks from the south and is involved in folds overturned to the north; tilted younger Pleistocene alluvial-fan deposits, dipping as much as 45° N, rest on the truncated beds of the Tulare Formation, which have been overturned to dip 25° south.

Throughout the southern part of the San Joaquin Valley the Tulare appears to be conformable on the underlying marine upper Pliocene, and is folded with it in the Kettleman Hills and Elk Hills anticlines. Northward from Panoche Creek, however (Fig. 7), it rests unconformably on all older formations (Anderson and Pack, 1915, p. 101; Reiche, 1950, p. 6; Briggs, 1953, p. 48). Within the foothills, patches of nearly flat-lying Tulare rest on a surface of low relief bevelled across steeply dipping older rocks; they are folded into dome-like structures with dips of 5°-15° on their flanks and amplitudes of 300-450 m (Christensen, in press a). Along the front of the foothills, the Tulare dips eastward 30°-50° parallel to the bedding in the older formations, in a sharp monocline that flattens abruptly eastward beneath the alluvium of the Great Valley (Fig. 6). In the range-front Monocline the Tulare Formation is 180-700 m thick and includes the Corcoran Clay member, described below (Carpenter and Long, 1963).

QUATERNARY DEPOSITS BENEATH THE FLOOR OF THE SAN JOAQUIN VALLEY

The Quaternary deposits beneath the valley range in thickness from a few meters on the east edge of the valley to 700-1,500 m along the valley axis. As much as 5,000 m of alluvium is reported to overlie upper Pliocene marine sediments beneath Buena Vista Lake at the south end of the valley (Davis *et al.*, 1959, quoting De Laveaga, 1952).

The alluvium has been investigated in detail by the U.S. Bureau of Reclamation and the U.S. Geological Survey by means of electric logs, drillers' logs, and a large number of continuous rotary-drill cores of the alluvial deposits. The results of these investigations are summarized in Davis *et al.* (1959). The alluvium on the east side of the valley was deposited by rivers from the Sierra Nevada and generally consists of well-sorted clean sand and sandy gravel. Numerous layers of red sand and silt associated with iron-silica hardpans, thought to be soil zones, have been encountered in this alluvium. The alluvium grows finer westward and grades into sections of silt and clay, in which recognizable soil zones are lacking. Alluvium in the western part of the valley is mainly poorly sorted silt and silty sand and gravel derived from the Coast Ranges and deposited by ephemeral streams or as mudflows.

The Corcoran Clay Member of the Tulare Formation, a diatomaceous silty-clay layer 3-50 m thick, underlies an area of about 13,000 km² in the San Joaquin Valley, at a depth of 60-270 m beneath the surface (Frink and Kues, 1954; Davis *et al.*, 1959, p. 76). Along the east front of the Coast Ranges, the Corcoran Clay Member crops out west of Tracy (Reiche, 1953) and south of Los Banos (Long and Carpenter, 1963). At both outcrops, the Corcoran Clay Member is interbedded in alluvium of the Tulare Formation and is therefore a member of that formation.

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North of the Kings River the alluvium above the Corcoran Clay Member is generally yellow or brown as a result of oxidation of some of its iron, but south of the Kings River the fine-grained alluvium beneath the center of the Valley is blue or gray, and its iron is in the ferrous state. Most of the alluvium beneath the Corcoran Clay Member throughout the valley has its iron in the ferrous state. The ferrous-iron-bearing alluvium is thought to have been deposited under marshy or lacustrine conditions, and the brown oxidized alluvium to have been deposited on the surfaces of well-drained alluvial fans (Davis *et al.*, 1959). Thus the San Joaquin Valley before Corcoran Clay Member time was predominantly marshy, and afterward marshy conditions persisted only along the valley axis and at the southern end.

The present rate of alluviation on the Arroyo Ciervo fan, about 20 km south of Panoche Creek on the west side of the San Joaquin Valley, on the basis of data of Bull (1964b, p. 36), is approximately 0.45 m per 1,000 years. The Corcoran Clay Member beneath this fan is overlain by approximately 200 m of alluvium.

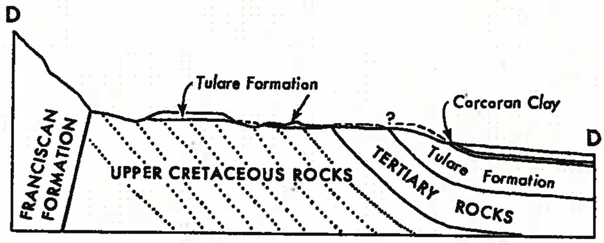

Figure 6. Diagrammatic cross-section of the eastern margin of the foothills of the Coast Ranges south of Los Banos, showing relation of Tulare Formation and Corcoran Clay to underlying rocks. Compiled from Long and Carpenter (1963) and Briggs (1953, Pl. 3). For location see Figure 5.

AGE OF THE TULARE FORMATION

The age of the Tulare Formation and the Corcoran Clay Member has been a matter of debate. Arnold and Anderson (1910, p. 153) thought that the Tulare represented a time-span from lower Pliocene to Pleistocene. Barbat and Galloway (1934) assigned the marine San Joaquin Formation beneath the Tulare to the lower Pleistocene, on the basis of the appearance of cold-water fossils in the top of the underlying Etchegoin Formation, thus placing the Tulare definitely in the Pleistocene, as it overlies the San Joaquin at its type locality. Woodring *et al.* (1940) placed the lower part of the Tulare in the Pliocene on the basis of a large number of extinct freshwater mollusks in the Lower

Amnicola Zone, and they considered the upper part of the formation to extend into the Pleistocene. K. E. Lohman (quoted by Frink and Kues, 1954, p. 2364, and by Davis *et al.*, 1959, p. 77) placed both the Corcoran Clay Member and the lower Tulare in the Pliocene because of the number of extinct diatoms that had not been reported from formations younger than Pliocene.

Durham *et al.* (1954, p. 69) report a Blancan fauna, including *Equus* (*Plesippus*), *Castor*, *Odocoileus*, and *Pliomastodon*, from the San Joaquin Formation, and they point out that correlation of the Blancan with the Villefranchian places the San Joaquin in the Pleistocene according to the definition of the 1948 International Geological Congress. (However, see Hibbard *et al.*, this volume, for another view.) In 1964, Charles Hall of the U.S. Bureau of Reclamation discovered vertebrate remains in a canal excavation in the Corcoran Clay Member about 20 km south of Los Banos. According to John Mawby (oral communication, 1964) this fauna includes remains of *Equus*, a camel, and mammoth that place it in the Irvingtonian (middle Pleistocene) or Rancholabrean (upper Pleistocene), and therefore the Corcoran Clay Member is Pleistocene.

Correlatives of the alluvial formations in the Turlock area have been identified along the San Joaquin River near Fresno by R. J. Janda (oral communication, 1963). A deposit of water-laid pumiceous ash at Friant was found by Janda to lie near the top of alluvial deposits correlated by him with the Turlock Lake Formation. A potassium-argon date on this ash by G. B. Dalrymple (oral communication, 1963) of 600,000 ± 20,000 years establishes the lower Pleistocene age of the Turlock Lake Formation. Janda traced the ash westward along bluffs of the San Joaquin River and found it to coincide in position with an ash recognized by Frink and Kues (1954) lying directly above the Corcoran Clay Member. Thus the Corcoran is about 600,000 years old, an age in agreement with its vertebrate fossils, and in approximate agreement with current rate of accumulation of alluvium on the west side of the San Joaquin Valley.

Corcoran Clay

ALLUVIAL FORMATIONS EAST OF THE DELTA REGION

The geology and ground-water resources of the area lying immediately east of the Delta region were investigated by Piper *et al.* (1939) (see Fig. 5 for location). They divided the late-Cenozoic deposits into the following formations, from youngest to oldest:

1. Alluvium beneath the present stream channels and beneath floodplains entrenched into the youngest alluvial fans, regarded as Recent in age.
2. The Victor Formation, as much as 38 m thick, consisting of sand, silt, and gravel, which underlies the youngest alluvial fans of the Mokelumne and Cosumnes Rivers.
3. The Arroyo Seco Gravel, up to 6 m thick, a pediment gravel mantling the dissected Arroyo Seco pediment along the west base of the Sierra Nevada.
4. The Laguna Formation, 120 m of poorly bedded stream-borne silt and sand with some gravel and clay, of presumed Pliocene age but possibly early Pleistocene in part, and unconformably underlying the Arroyo Seco Gravel.
5. The Mehrten Formation, andesitic conglomerate and mudflows of Pliocene and Miocene age.

Davis and Hall (1959, p. 12) correlate their Modesto and Riverbank Formations with the Victor Formation, and their Turlock Lake Formation with the Laguna. They do not find the Arroyo Seco Gravel in the region south of the Mokelumne River.

THE ALLUVIAL FORMATIONS OF THE SACRAMENTO VALLEY

Lindgren (1894) and Lindgren and Turner (1895) recognized dissected Pleistocene gravels with red hardpan soils that they correlated with glaciation in the Sierra Nevada, and undissected alluvium beneath stream channels and the central basin lands. In 1905 Diller defined the Red Bluff Formation, red-weathered and dissected alluvium that he also correlated with glacial advances in the mountains. In his ground-water study of the Sacramento Valley, Bryan (1923) traced the older alluvium around the valley and showed that it is equivalent to the Red Bluff Formation. Russell and VanderHoof (1931) showed that the lower part of Diller's Red Bluff Formation (Bryan's Older Alluvium) is actually a separate formation, on which the younger gravels, for which the name Red Bluff was retained, rest unconformably. They gave the name Tehama to the older formation.

Anderson and Russell (1939) have summarized the geology of the Tehama Formation; according to them, it consists of a 30-180-m sequence of poorly sorted massive sandy silt, sand, and silty gravel, of fluviatile origin, derived from the Coast Ranges and Klamath Mountains to the west and northwest. It rests on a smooth surface planed across steeply dipping Cretaceous rocks on the west side of the Sacramento Valley, and this surface, projected westward, intersects the high mountains of the Coast Ranges at altitudes of 750-900 m, approximately half their total altitude. This suggests that the Tehama may have been deposited as a pediment formation, although it is now locally warped and folded and has an average dip of 4° to the east.

Along the Sacramento River between Redding and Red Bluff, the Tehama Formation interfingers eastward with the Tuscan Formation, a sequence of andesitic tuffs, breccias, and volcanic sediments, locally as much as 300 m thick, which mantles the west flank of the Cascade Mountains east of northern Sacramento Valley and was apparently derived from eruptions near the site of Mt. Lassen (Diller, 1895; Anderson, 1936; Anderson and Russell, 1939). A prominent pink dacitic tuff, the Nomlaki Tuff, occurs near the base of both formations and establishes their contemporaneity.

Anderson and Russell regarded the Tehama and Tuscan as upper Pliocene on the basis of fossils collected from near the Nomlaki Tuff horizon (VanderHoof, 1933). Stirton (1936) assigns the Tehama fauna to the Blancan. Recently a potassium-argon date of 3.3 million years has been obtained from the Nomlaki Tuff near the base of the Tuscan approximately 65 km northeast of the Tehama fossil localities and on the opposite side of the Sacramento Valley (Evernden *et al.*, 1964).

Olmsted and Davis (1961) have traced the formations mapped by Piper *et al.* (1939) in the Mokelumne area northward along the east side of the Sacramento Valley and find that the Laguna Formation corresponds with Bryan's Older Alluvium, underlying the "red lands" or dissected uplands, and that the Victor Formation corresponds to Bryan's Younger Alluvium under the essentially undissected fan surfaces.

THE QUATERNARY OF THE SOUTHERN COAST RANGES

GENERAL STATEMENT

The Quaternary formations of the southern Coast Ranges record phases of a period of orogenic activity that extended from mid-Tertiary to the present. Deformed sediments exposed along the margins of structural valleys have been assigned to the upper Pliocene and lower Pleistocene. A few of these deposits along the coast are marine, but the great bulk are of continental origin and consist of poorly sorted lenticular gravel, sand, and clay, with occasional marl beds. They were derived mostly from highlands that rim the basins in which they occur. In the following pages the lithology and stratigraphic and structural relations of the formations are discussed, with the exception of the Tulare Formation, which was covered in the preceding section on the Great Valley.

The continental formations are sparsely fossiliferous; some have produced no diagnostic fossils. Many of the formations rest conformably on marine Pliocene rocks; others contain Pliocene faunas in their lower parts and Pleistocene faunas in their upper parts.

These moderately deformed Plio-Pleistocene formations are offset by major faults. Much of the present topography was developed after they were deformed. Throughout the northern and western parts of the southern Coast Ranges they rest with profound angular unconformity on tightly folded and deeply eroded older rocks. Along the border with the San Joaquin Valley, and in parts of the upper Salinas and Santa Maria basins, they are parallel to and apparently conformable upon marine Pliocene formations, and their lower contact marks the withdrawal of the sea from this part of California. The boundary between areas of conformity and unconformity is shown on Figure 7. The region of conformity is also the region of major oil-fields and has received the bulk of geologic work on the Coast Ranges. Hence the concept of a major mid-Pleistocene orogeny, more intense than any since the mid-Cretaceous, grew to dominate geologic thought about coastal California.

The youngest marine sediments are at the top of the San Joaquin Formation at the south end of the San Joaquin Valley. During the marine withdrawal that closed the San Joaquin Embayment, a major shift in drainage in the Coast Ranges took place. The strait that connected the southern end of the San Joaquin Valley to the Pacific Ocean, whose exact position is uncertain, was blocked by the rising Coast Ranges, and a new outlet to the sea for the San Joaquin Valley was established via San Francisco Bay, whose system of depressions probably came into existence about this time. According to Jon Galehouse (oral communication, 1964), the Salinas River has apparently extended itself headward along a structural valley to capture drainage of the southern Coast Ranges that formerly flowed south and east toward the southern San Joaquin Embayment.

The volume of the Plio-Pleistocene formations represents comparable volumes of erosion and presumably uplift in the mountain areas. Local angular unconformities, where rocks of Miocene or Pliocene age overlap onto the folded Cretaceous rocks, are common in the uplifted mountain areas. Within some of the basins, particularly the San Joaquin Valley, the formations are parallel, and unconformities in the Tertiary succession, if present, involve only minor amounts of tilting. The pattern of Miocene and Pliocene unconformities is repeated at the base of the deformed Plio-Pleistocene succession, with much more extensive preservation of remnants of the deformed Plio-Pleistocene sediments in the uplifted areas, probably because insufficient time has elapsed to remove them.

Generally the maximum tilting of the formations is near the borders of the ranges; on the east flank of the Diablo Range, as pointed out in the section on the Great Valley, the Tulare is tilted into a monocline on the range front, but it is nearly flat-lying both where it is preserved as remnants in the foothills and in the valley to the east (Fig. 6). The pattern of unconformities suggests repeated pulses of uplift and deformation within the mountain blocks throughout the upper Cenozoic, with deformation concentrated along their margins, and rather steady subsidence of the basins; the mountain areas may be growing at the expense of the basins.

Recent work by Christensen (in press a) has shown that the map pattern of Pleistocene deformation in the Coast Ranges is not linear but consists of a number of broad relatively flat domes centered for the most part on the areas that were already positive at the beginning of Pleistocene time. These domes bear no apparent relation to the major strike-slip faults of the region; the latter slice through domes and basins indiscriminately.

THE DEFORMED PLIO-PLEISTOCENE FORMATIONS

Fossiliferous marine sandstone and siltstone 1,500 m thick, dipping 15°-75° NE and exposed in seacliffs for 6 km south from San Francisco, have been named the Merced Formation (Lawson, 1893; see also Lawson, 1914; Ashley, 1895; Martin, 1916; Glen, 1959; Higgins, 1961). According to Glen (1959), his upper Merced Formation is Pleistocene. This view is also held by J. Wyatt Durham (oral communication, 1965), who feels that the Plio-Pleistocene boundary may even fall at some place within the upper part of Glen's lower Merced.

Deformed poorly consolidated gravels, totalling perhaps 1,500 m and dipping 5°-25° NE, are exposed along the south and west sides of Livermore Valley (Huey, 1948; Hall, 1958); they were named the Livermore Gravels by Vickery in 1925 (unpublished report quoted by Huey). They rest unconformably on tightly folded rocks as young as late Hemphillian (Evernden *et al.*, 1964, p. 164) and contain an Irvingtonian (middle-Pleistocene) fauna (Savage, 1951, p. 284).

Deformed gravels occur around the margins of the Santa Clara Valley, a structural trough whose drowned north end is San Francisco Bay. In the northeastern part of the valley these are known as the Irvington Gravels (Hall, 1958) and are the type locality for the middle-Pleistocene Irvingtonian land-mammal age (Savage, 1951). Around San

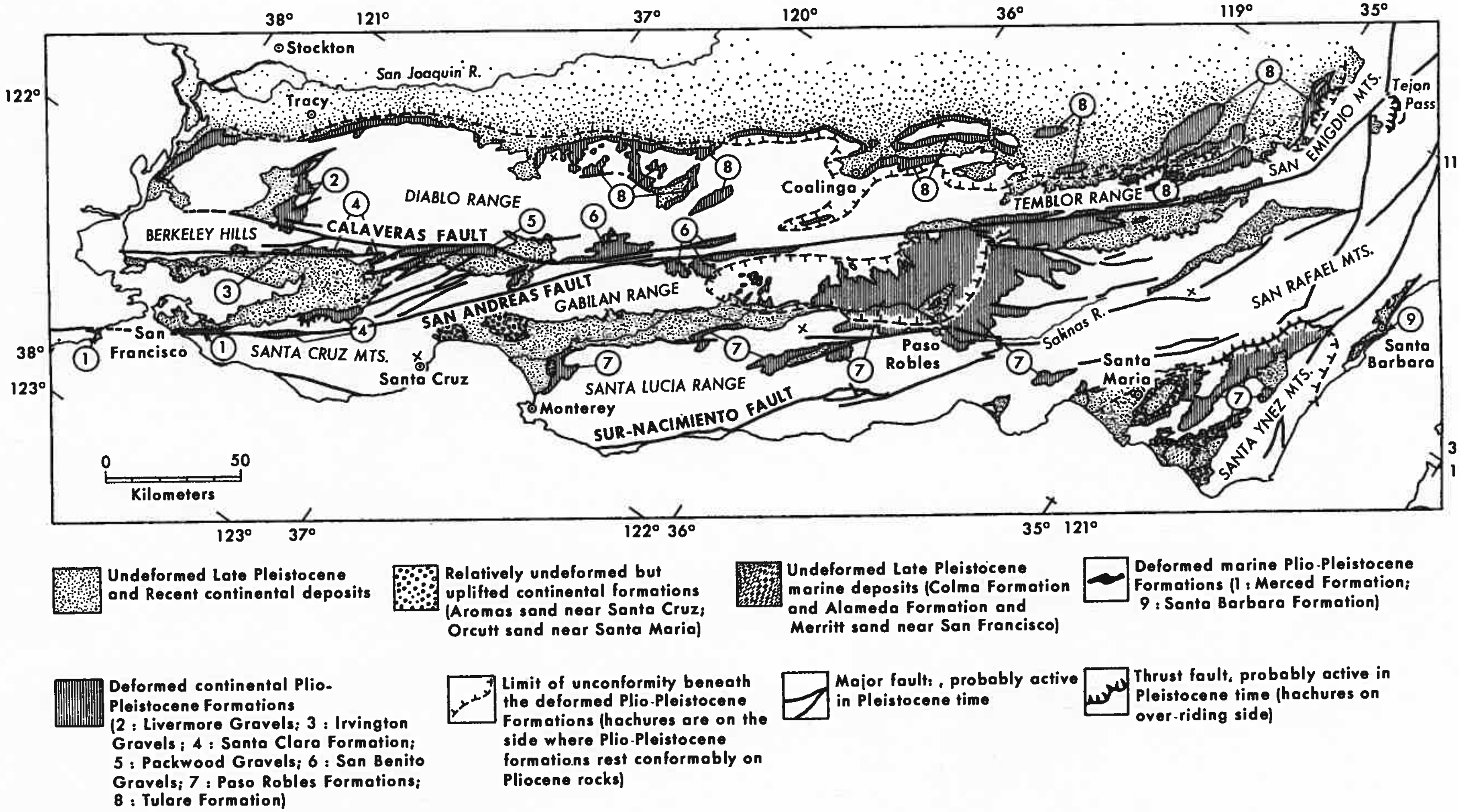

Figure 7. Map of the southern Coast Ranges showing distribution of Plio-Pleistocene and Quaternary formations, major faults, and limits of unconformity at the base of the Plio-Pleistocene formations. Compiled from Jennings (1958, 1959), Jennings and Strand (1958), Jennings and Burnett (1961), Kundert (1955), Huey (1948), Hall (1958), Anderson and Pack (1915), Crittenden (1951), Ortalda (1949), California State Water Resources Board (1955).

Jose and along the west side of Santa Clara Valley these are known as the Santa Clara Formation, which may be as much as 1,000 m thick below the center of the valley (Branner *et al.*, 1908; California State Water Resources Board, 1955; Cummings *et al.*, 1963; Crittenden, 1951). Between San Jose and Gilroy, gravels correlated with the Santa Clara Formation or slightly older, and dipping 30°-90° E or locally overturned, make up the hills along the east side of the Santa Clara Valley. These are known as the Packwood Gravels (Ortalda, 1949; Crittenden, 1951; California State Water Resources Board, 1955). They total 1,200 m in thickness and contain interbedded basalt. At the south end of Santa Clara Valley and extending southward along the San Benito River and San Andreas Fault Zone are the San Benito Gravels, 450-650 m of poorly consolidated, moderately deformed early-Quaternary and late-Pliocene conglomerate (Wilson, 1943, p. 246).

The extensive Plio-Pleistocene deposits in the upper Salinas Valley and Santa Maria Basin are known as the Paso Robles Formation (Fairbanks, 1898). The Paso Robles characteristically contains abundant pebbles of Miocene diatomaceous shale and siliceous mudstone. The Paso Robles Formation underlies an area of 4,000-5,000 km^2 in the upper Salinas Basin, where it is mainly flat-lying and 100-600 m thick (Taliaferro, 1941, 1943; Dibblee, 1962) and was probably once continuous over an area 220 km long and 45 km wide. In the Santa Maria Basin it has been mapped over a triangular area 70 km long and 40 km wide; it ranges from 100 m to 1370 m in thickness (Woodring and Bramlette, 1950; Dibblee, 1950; Upson and Thomasson, 1951; Nelson, 1925). In the center of the basins the Paso Robles Formation is conformable on the underlying marine Pliocene, and deposition was probably continuous from Pliocene time into the Pleistocene (Taliaferro, 1941, 1943; Woodring and Bramlette, 1950). Along the margins of these basins the Paso Robles rests on the underlying Pliocene with marked angular unconformity and overlaps it to rest on Miocene to Cretaceous rocks.

RELATIVELY UNDEFORMED QUATERNARY DEPOSITS OF THE SOUTHERN COAST RANGES

The structural and erosional valleys formed during the deformation of the Plio-Pleistocene formations are underlain by relatively undeformed deposits of presumed late-Quaternary age. In the centers of the valleys these deposits may grade downward into the lower Pleistocene deposits, but around the margins they rest on them unconformably or rest directly on an irregular surface carved on much older rocks.

The late-Quaternary deposits have been studied most thoroughly in the San Francisco Bay region, where they are of importance as foundations for highways, bridges, and buildings. Seven formations have been recognized, ranging from a few meters to a few hundred meters in thickness, and in part contemporaneous (Lawson, 1915; Louderback, 1951; Trask and Rolston, 1951; Radbruch, 1957; Schlocker *et al.*, 1958). The oldest is the Alameda Formation, consisting of sand, sandy clay, clay, and fine gravel, which extends to a depth of 300 m southeast of Oakland but is generally about 60-70 m thick. It contains plant fragments, a Rancholabrean vertebrate fauna, but no marine fossils, and it is presumably terrestrial. Its upper surface is an irregular erosion surface with as much as 15 m of relief, on which a well-developed soil was formed.

Overlying the Alameda Formation are two formations, first the San Antonio, a predominantly marine dark glauconitic(?) clay with shell beds, and then the Posey, probably non-marine. They are separated by an irregular erosional surface on which a soil was formed; they may represent two periods of rising sea level, and the erosional unconformities that bound them may represent periods of falling sea level resulting from continental glaciation elsewhere. Radbruch (1957) groups these two formations with the Alameda Formation.

Overlying these are two formations that represent a third rise of sea level. Beneath San Francisco Bay and parts of Oakland and Alameda is a beach and dune sand, the Merritt Sand, which fills valleys cut in the Posey Formation and is itself dissected. It grades eastward into the Temescal Formation, which consists of alluvial-fan deposits that are in part warped and dissected. Subsequent to the deposition of these formations, sea level again fell, this last lowering probably corresponding to the Wisconsin Glaciation.

During and after the postglacial rise in sea level, as much as 30 m of bay mud with low shear strength and high porosity have accumulated on the bay floor, partially burying an irregular topography carved on the Pleistocene formations.

Deposits of flat-lying sand, silt, and clay, found around the city of San Francisco up to altitudes of 150 m, and called the Colma Formation (Schlocker *et al.*, 1958) may represent one or several high stands of sea level.

Unconsolidated alluvium beneath Santa Clara Valley southeast of San Francisco Bay extends as much as 240 m below sea level (Poland and Green, 1962), but the lower part may be in the Santa Clara Formation. According to the California State Water Resources Board (1955), the alluvium is separated from the underlying Santa Clara Formation by a prominent red oxidized zone. One horizon in the alluvium, about 90 m below the surface, contained marine mollusks. Near Gilroy toward the south end of Santa Clara Valley, freshwater mollusks and peat from fresh water tule swamps were encountered at 100 m below sea level. These younger alluvial deposits indicate that the trough of San Francisco Bay and Santa Clara Valley has subsided 210 to 300 m in late-Pleistocene time, but that sedimentation was sufficiently rapid to keep the sea out of all except its north-central portion.

At the north end of the Salinas Valley is a deposit of red cross-bedded sand, the Aromas Red Sand, of late-Pleistocene age (Allen, 1946, p. 43-45). It is as much as 225 m thick and occurs as high as 240 m above sea level. It has been uplifted, tilted slightly westward, and deeply dissected. An anomalous beheaded valley cuts across the Aromas Red Sand and leads to Elkhorn Slough, a deep meandering indentation at the head of Monterey Bay. This valley is interpreted as a tilted and abandoned course of the San Benito River. Its lower course is drowned, and it is therefore older than the last rise of sea level.

The lower part of the Salinas Valley is a structural trough underlain by alluvial deposits at least 150 m thick. At the mouth of Salinas Valley, the alluvium beneath the valley floor contains two prominent clay layers that act as aquacludes; the upper layer is about 55 m below sea level and the lower about 120 m below sea level. Each layer extends about 40 km up the valley, and the sands between them crop out on the walls of the submarine canyon at the head of Monterey Bay (Manning, 1963). The clay layers probably represent estuarine conditions in the Salinas Valley during interglacial high sea-level stands, and the intervening sands represent alluvial conditions when the sea was at or below its present level.

In the Santa Maria Basin, a slightly deformed deposit of reddish iron-cemented sand with interbedded gravel lenses, similar to the Aromas Red Sand and called the Orcutt Sand, rests unconformably on the folded and eroded Paso Robles Formation (Woodring and Bramlette, 1950, p. 51; Dibblee, 1950, p. 50; Upson and Thomasson, 1951, p. 39). It has a maximum thickness of 60 m and locally reaches altitudes of about 300 m. It is mildly deformed, with dips as high as 12°-15° on the flanks of anticlines in the Santa Maria Basin, and it appears to grade seaward into marine terrace deposits at altitudes of about 120 m.

MARINE TERRACES

The exposed coasts of the southern Coast Ranges are marked by flights of well-developed marine terraces. The most spectacular terraces are at Santa Cruz, but terraces are also well preserved in the Santa Lucia Mountains near Monterey and San Simeon and in the area west of Pismo Beach. Figure 8 is a plot of the heights of marine terraces along the southern Coast Ranges. The scale of this figure is deliberately small, as the accuracy of the determinations is not great and it is not certain from early descriptions just what parts of the terraces were measured.

As many as five or six terraces have been recognized on some favorable sites, ranging in altitude to 250 or 300 m; marine deposits and pholad borings on even the highest of these terraces confirm their marine origin. Higher terraces have been postulated on the basis of accordant level stretches of ridge crests and summit flats, but they have not been confirmed, and in consideration of the tectonic activity of the Coast Ranges it is doubtful that confirmation in the absence of marine deposits will ever be possible. Where the marine terraces are associated with the deformed Plio-Pleistocene formations, they transect these formations.

Bradley (1957) showed that the marine terraces at Santa Cruz were cut during periods of rising sea level, and that their mantle of marine terrace deposits was laid down during falling sea level. Thus each terrace represents an oscillation of sea level with respect to the adjacent land. He showed further (1956) that the lowest marine terrace at Santa Cruz (the 30-m terrace) was formed more than 39,000 years ago and is probably of Sangamon age. More recently Blanchard (1963) has dated shell material from this terrace by the Th^{230}/U^{238} method at 122,000 ± 9,000 years and by the Ra^{226}/U^{238} method at 110,000 ± 9,000 years.

Davis (1933) pointed out that the marine terraces along the California Coast slope gently seaward, as does the present wave-cut platform, and that the back parts of the marine terraces are mantled by thick deposits of colluvium and alluvium. Neither the front edge nor the back edge of the present-day topographic terrace surface can be used for correlation or for estimating uplift. The buried shoreline angle at the base of the sea-cliff, cut probably at the moment of greatest advance of the sea before withdrawal from the terrace surface, is the only suitable datum point for purposes of correlation. This shoreline angle is exposed at wide intervals in roadcuts or along stream canyons, and elsewhere it must be estimated from exposed terrace features or probed for by seismic methods or wells. It is not certain whether the terrace heights reported in the earlier of the sources for Figure 8 are for the shoreline angle or for some other part of the terrace. Failure to locate the shoreline angle may account in part for the differences in height of the same terrace reported by different observers.

The higher marine terraces are moderately deformed, and their shoreline angles rise and fall a few meters to a few tens of meters per mile, parallel to the shore. The lowest terraces are much less deformed, and for long distances their shoreline angles maintain the same altitude. The lowest terrace of the Santa Cruz Mountains is about 30 m above sea level (Bradley, 1957 and personal communication, 1964), and in the Santa Lucia Mountains the lowest terrace is about 12 m above sea level, although a 6-m terrace was recognized locally (Trask, 1926).

The continuity of the terraces is best established in the Santa Cruz Mountains, where individual terraces can be traced for distances of several kilometers. As Figure 8 shows, even the lowest terraces are considerably deformed locally, their shoreline angles rising and falling several tens of meters in a few kilometers. (The apparent sharpness of the flexure in the terraces at Capitola results from the projection of nearly east-trending shoreline angles onto the plane that trends N 27° W.) It is clear from the figure that in the Santa Cruz Mountains the terrace heights do not represent eustatic sea-level changes but probably result largely from uplift and deformation of the mountains.

Terraces on the steep coast of the Santa Lucia Mountains are rarely continuous enough for reliable correlation.

The terraces in the Point Sal and Santa Ynez River areas are cut into the sides of mountains carved from the cores of anticlines involving the deformed Paso Robles Formation and Orcutt Sand, formations of early- to middle-Pleistocene age. Thus these terraces, even the 240-m terrace, must be late Pleistocene in age. The Paso Robles Formation is continental in origin, and the Orcutt Sand is largely continental, so the terraces may represent a period of submergence after early-Pleistocene time.

There are no marine deposits in the valleys of the southern Coast Ranges or on the interior flanks of the mountains to represent the high sea-level stands of the marine terraces (Howard, 1954). In structural basins such as the Salinas and Santa Clara Valleys the alluvium is almost entirely continental. The ranges are not conspicuously asymmetric, and topography on opposite sides of the coastal divides appears to be of comparable maturity and chronologic

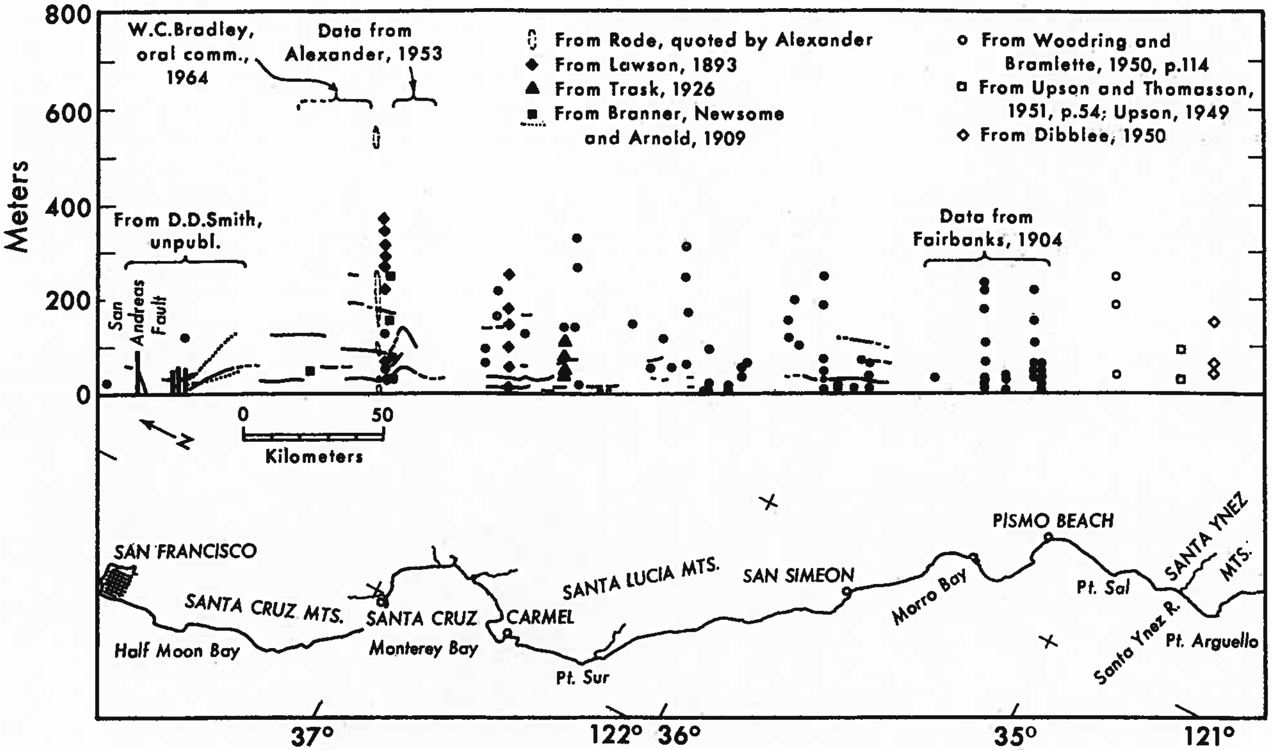

Figure 8. Marine terraces between Point Concepcion and San Francisco, projected onto a vertical plane between Lands End and Point Concepcion. Compiled from 1:24,000 topographic maps of the U.S. Geological Survey, original field surveys, and various published and unpublished sources.

age, so relative uplift of a narrow belt immediately adjacent to the shore can be ruled out as an explanation for this anomaly. At present, this contradiction between the coastal evidence for recent emergence amounting to a few hundred meters, and interior evidence of continuously continental conditions at low altitudes has no explanation.

Subsequent to the cutting of the lowest marine terrace (about 100,000-130,000 years ago; Blanchard, 1963) the sea withdrew to a level about 100 m below present sea level, as a result of ice accumulation of the Wisconsin glaciation. Large streams excavated steep-walled canyons through the flat terraces, canyons graded to lower sea level (Upson, 1949). Postglacial sea-level rise has resulted in the drowning of these valleys, which are now filled with alluvium that extends as much as 24-30 m below sea level, and the valleys, therefore, have broad, flat floors, and most streams enter the ocean via lagoons. San Francisco Bay, the largest of the valleys excavated to lowered sea level, has not yet been filled (Louderback, 1951; Trask and Rolston, 1951).

The Northern Coast Ranges and the Klamath Mountains

INTRODUCTION

The Quaternary history—in fact most of the Cenozoic history of the northern Coast Ranges and Klamath Mountains is one of erosion. Geologic mapping (much of it still reconnaissance) for the entire region has been summarized by Irwin (1962) and is depicted on the new sheets of the Geological Map of California (Jennings and Strand, 1960; Koenig, 1963; Strand, 1962, 1963). Figure 9 shows the *gipfelfluhr* (surface generalized from summit altitudes) for northwestern California; it also shows the distribution of Plio-Pleistocene and Quaternary deposits.

A. C. Lawson (1894) and J. S. Diller (1902) were the first to study the geomorphology of the northern Coast Ranges and Klamath Mountains. They were enthusiastic proponents of the concept of the erosion cycle that had been recently developed by Davis, and they were led by the apparent accordance of summit levels throughout these mountains, when viewed from a high point, and by the numerous summit flats, to postulate a series of pauses in the supposed bodily uplift of these ranges, when partial peneplains were cut. The oldest of these was the Klamath Peneplain (Diller, 1902, Wells *et al.*, 1949; Irwin, 1960), above which the highest peaks of the Klamath Mountains were supposed to rise in isolated clusters. However, the *gipfelfluhr* shown in Figure 9 does not have that uniformity of altitude one would expect in a peneplain.

THE TERTIARY SHORELINE

Continental and marine rocks of Miocene age near Crescent City (Diller, 1902; Maxson, 1933; Cater and Wells, 1953), continental Oligocene sediments in the Weaverville area (Hinds, 1933; MacGinitie, 1937), and marine Miocene rocks near Round Valley (Clark, 1940) establish points on a Miocene shoreline that extended diagonally across the northern Coast Ranges from Crescent City to the vicinity of Vacaville, where the northernmost Miocene sediments on the west side of the Sacramento Valley are found (Weaver, 1949). Land lay to the northeast of this line; to the southwest was probably an archipelago.

DEFORMED PLIO-PLEISTOCENE FORMATIONS

Within the northern Coast Ranges are many small lowlands and plains 1-10 km broad. Although not nearly so large or continuous as the broad structural valleys of the southern Coast Ranges, they, also, are underlain and bordered by

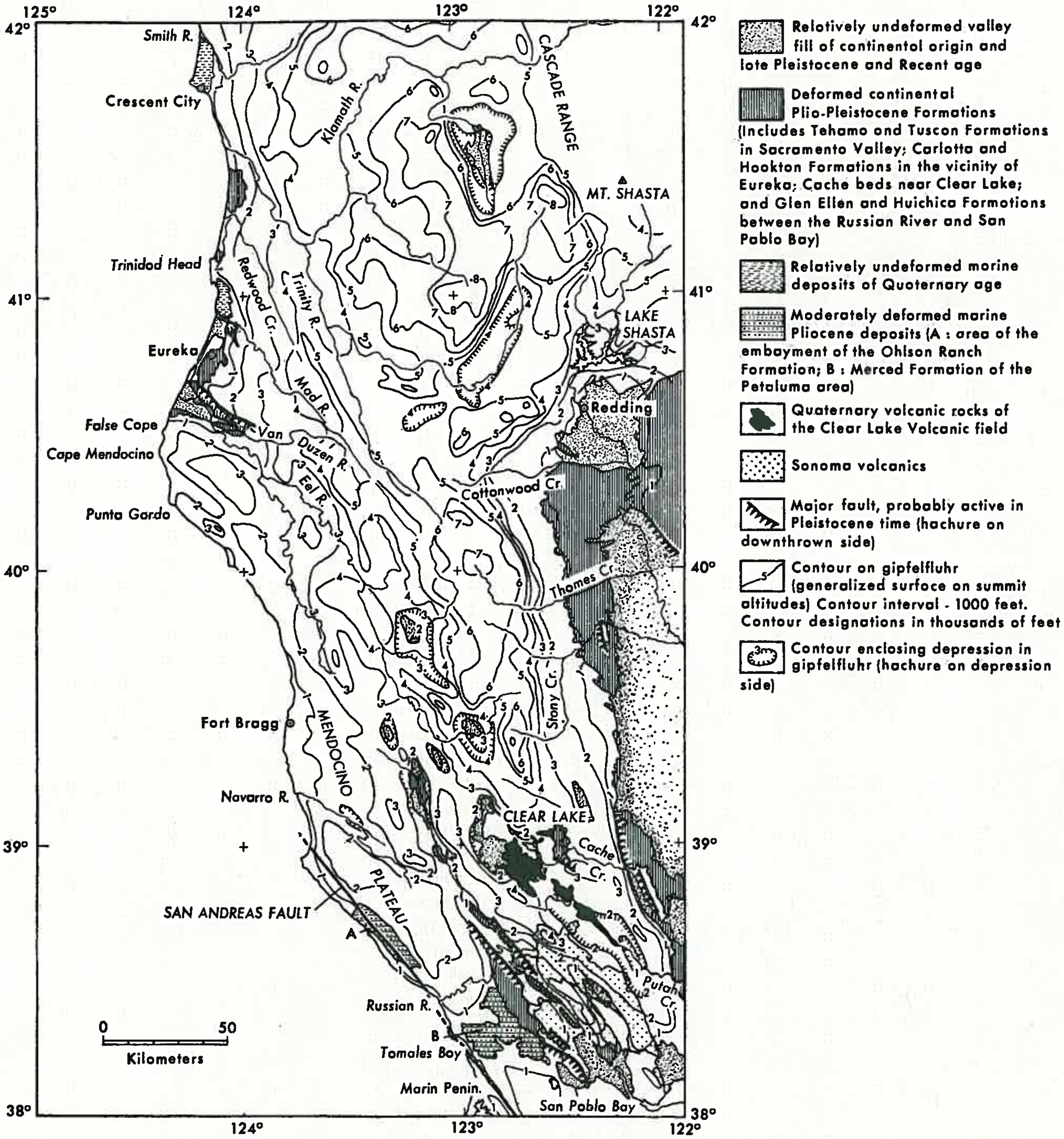

Figure 9. Map of the northern Coast Ranges and Klamath Mountains in California, showing distribution of Plio-Pleistocene and Quaternary formations and contours on the *Gipfelfluhr* (generalized surface on summit altitudes). Compiled from Strand (1962, 1963), Koenig (1963), Jennings and Strand (1960), and Army Map Service 1:250,000 topographic maps of Weed, Redding, Eureka, Ukiah, and Santa Rosa Quadrangles.

deformed sedimentary rocks of Pliocene and early-Pleistocene age. In some of these basins the Quaternary formations are the top of a thick succession of upper Cenozoic rocks. In most of the basins, however, the Plio-Pleistocene sediments rest with profound unconformity on Cretaceous rocks or on the Franciscan Formation. Marine formations along the coast are abundantly fossiliferous, and their stratigraphic age is known. Inland, the formations are mainly continental and have yielded fossils in only a few places. Interbedded volcanic rocks give the hope, already partly realized, of establishing absolute ages for many of these formations. These deformed rocks establish the maximum age of the latest period of folding and faulting in the northern Coast Ranges.

In the extreme northwest corner of California, the coastal flat around Crescent City is underlain by the St. George Formation, which consists of about 130 m of massive siltstone and shale with thin discontinuous sand beds, of lower Pleistocene age, dipping about 12° NE at its only exposure (Diller, 1902, p. 32; Maxson, 1933; Back, 1937, p. 20).

Deformed sediments of Miocene to Pleistocene age occupy several structural basins in a belt 15-50 km wide extending from 90 km south of Eureka to 65 km north of Eureka. They demonstrate that this belt was largely submerged during much of Pliocene time and has been considerably deformed since then. These Cenozoic sediments are in structural basins a few kilometers wide and a few tens of kilometers long that trend northwesterly. The largest includes the lower Eel River valley and the coastal lowland between the mouth of the Eel and the mouth of the Mad River. Approximately 4,200 m of sediments in this basin, named the Wildcat Group (Lawson, 1893), are predominantly marine; they have at their top 150-900 m of massive non-marine conglomerate and sandstone with some brackish and marine interbeds, of Pleistocene age, the Carlotta Formation (Ogle, 1953). The Wildcat Group is folded into a broad west-northwest-trending syncline whose flanks dip 35°-60° and are locally overturned. Cretaceous rocks overthrust the Wildcat Group on the north flank of the syncline.

Small patches of marine sediments downfaulted into the Franciscan, a few kilometers east of the Wildcat Basin along the Van Duzen River, southward on the Mattole, and southeastward on the South Fork of the Eel. (Ogle, 1953; MacGinitie; 1943; Strand, 1962), suggest that a considerable part of the northern Coast Ranges was submerged for 50 km inland from the present shore during at least some of Pliocene time. Ogle (1953) feels that parts of the intervening ridges stood as islands in the Pliocene sea.

In the southern part of the region shown in Figure 9, the coastal belt underwent mild deformation and uplift amounting locally to 450 m since late-Pliocene time, and the area east of the coastal belt was the site of late-Pliocene and Quaternary volcanism and was deformed into folds with amplitudes of several hundred to a thousand meters. The relatively slight deformation along the coast is indicated by two slightly deformed marine formations of late-Pliocene age, the Ohlson Ranch Formation (Higgins, 1960; Peck, 1960) (area A on Figure 9), and the Merced Formation (Johnson, 1943; Weaver, 1949; Travis, 1952; Gealey, 1950; Higgins, 1952) (area B on Fig. 9). These formations were deposited in coastal embayments that extended 8 to 24 km respectively eastward from the present shoreline and are now a few tens to 450 m above sea level. The Merced Formation interfingers eastward with the Sonoma Volcanics and associated continental deposits, the Glen Ellen and Huichica Formations (Weaver, 1949), which are faulted and folded. The interfingering relations help establish the pre-Quaternary paleogeography.

The Sonoma Volcanics are a pile of andesitic, basaltic, and rhyolitic tuffs and flows, with intercalated sediments, totalling 300-900 m in thickness and covering an area of 900 km^2 at the southern end of the northern Coast Ranges (Weaver, 1949; Travis, 1952; Cardwell, 1958; Kunkel and Upson, 1960; Koenig, 1963) (Fig. 9). Where they interfinger with the Merced Formation, both formations rest with angular unconformity on tightly folded beds of the Petaluma Formation, which Stirton (1939, 1952) and Axelrod (1944) regard as no older than middle Pliocene (see Cardwell, 1958, for a discussion). Farther east, the Sonoma Volcanics rest with angular unconformity on all older rocks.

Weaver (1949, p. 34) regarded the Merced fauna as middle Pliocene in age, but it is now regarded as upper Pliocene (Stirton, 1952). The Sonoma Volcanics have produced a flora assigned by Axelrod (1944, 1957) to the Blancan (late Pliocene or early Pleistocene), and a diatomaceous unit within the Sonoma Volcanics contains numerous species in common with the assemblage at the base of the Tulare Formation, according to Lohman (quoted by Kunkel and Upson, 1960). More recently, a potassium-argon age of 3.4 million years has been obtained on tuff from the Sonoma Volcanics (Evernden and James, 1964).

The topography of the region of the Sonoma Volcanics is partly the result of the accumulation of the volcanic rocks and their resistance to erosion, and partly of the deformation following the eruption of the volcanics. This deformation involves continental gravels that rest on the Sonoma Volcanics with angular unconformity, the early-Pleistocene Glen Ellen and Huichica Formations, which dip locally as much as 60°.

Volcanism and deformation have affected the heart of the northern Coast Ranges throughout Quaternary time. Between the Sonoma Volcanics and Clear Lake, the Clear Lake Volcanic Field (Anderson, 1938; Brice, 1958) contains eruptive deposits that range in age and state of preservation from tilted basalt flows possibly interbedded in deformed early-Quaternary sediments to undissected dacite domes, basaltic cinder cones, and basalt and obsidian flows resting on the present landscape and apparently active in late-Quaternary time. Numerous hot springs and solfataras indicate that volcanic activity is continuing. Mt. Konocti, a perfectly preserved dacitic strato-volcano rising 900 m above Clear Lake, dominates the northern part of the volcanic field.

Clear Lake, less than 15 m deep, lies along the northern side of the volcanic field in a structural depression underlain by an unknown but presumably great thickness of Quaternary alluvium, lacustrine sediments, and tuffs. The lake discharges through Cache Creek, which flows eastward through deep gorges to the Sacramento Valley.

Deformation in the Clear Lake area is best demonstrated by the Cache Beds, which are about 2,000 m of light-gray thinly bedded silt with intercalated sand and gravel, grading upward into diatomite, marl, and thin limestone beds, and tuffaceous at the top (Brice, 1953; Anderson, 1936; Upson and Kunkel, 1955). The Cache Beds dip 20°-60° W toward Clear Lake and flatten westward. They have produced few fossils, but the ramus of a lower jaw of *Elephas*, identified by V. L. VanderHoof (Anderson, 1936a, p. 369), indicates that the formation is at least in part Pleistocene. Faults with several thousand meters of displacement appear to have been active during deposition of the Cache Beds. Presumably the Cache Beds accumulated in a predecessor of the Clear Lake basin, and the eastern end of this basin was uplifted and tilted west after accumulation of 2,000 m of sediment.

Deformed unfossiliferous continental deposits similar in degree of consolidation and stratigraphic position to the Cache Beds, the Glen Ellen Formation, and the Huichica Formation underlie eight small plains in the central part of the north Coast Ranges (California Division of Water Resources, 1958). Alluvial fills in several of these valleys extend 100-200 m below the level of their bedrock lips.

Anderson Valley at the head of the Navarro River presents a special problem in that deformed alluvial deposits of Plio-Pleistocene(?) age are exposed at the west end of the valley at altitudes of 60 m, yet 9 km to the west marine sands that may be equivalent to the Ohlson Ranch Formation cap the drainage divide south of the Navarro River at 460 m altitude, and marine terraces as high as 180 m are at the mouth of the Navarro 19 km to the northwest of Anderson Valley. There is no sign in Anderson Valley of marine deposits to correspond to these high sea-level stands, and geomorphic evidence of depression of the headwaters is lacking.

The Plio-Pleistocene Tehama Formation and the Pleistocene Red Bluff Formation, described in the section on the Great Valley, contain stratigraphic evidence suggesting that north of latitude 39° 30′ N the northern Coast Ranges have been bodily uplifted since late-Pliocene time about 350-540 m with respect to the Sacramento Valley on the east, and that this uplift involved tilting of the belt underlain by the Cretaceous monocline. The same sort of stratigraphic evidence suggests that south of latitude 39° 30′ N much more intense deformation has taken place since late-Pliocene time, resulting in monoclines and normal and thrust faults of several hundred meters displacement.

South of latitude 39° 00′ N the Cretaceous monocline may have been uplifted in Pleistocene time into an arch 10-15 km wide and 300-900 m above the country on either side.

COASTAL TERRACES AND THE CONTINENTAL SHELF

Marine terraces are well preserved on long stretches of the coast and are absent from other stretches. Terrace altitudes are summarized in Figures 10 and 11. The terraces can be traced longer distances and show more regularity in altitude

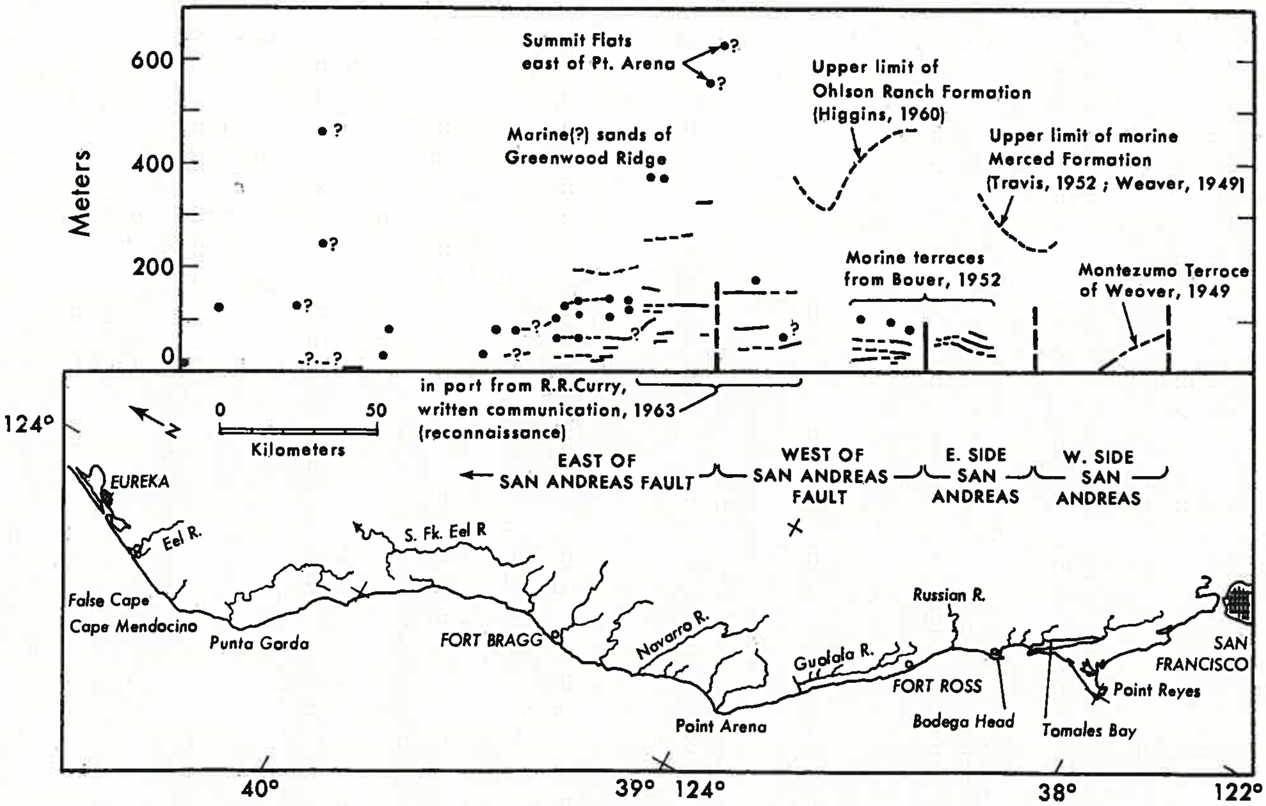

Figure 10. Marine terraces between the Golden Gate and Cape Mendocino, projected onto a vertical plane between Point Bonita and Cape Mendocino. Compiled from 1:24,000 and 1:62,500 topographic maps of U.S. Geological Survey, original field surveys, and various published and unpublished sources.

of shoreline angle here than they do in the southern Coast Ranges. Locally, however, they are considerably warped, and areas of greatest deformation are adjacent to the San Andreas Fault (particularly on its southwest side) and around Eureka and the mouth of the Eel River. The highest marine terraces are generally a hundred meters or so below the level of the upper Pliocene marine sediments (such as the Merced and Ohlson Ranch Formations) that cap ridge crests. Assuming relatively constant rise of the coast, these terraces should be early Pleistocene in age. Terraces are as high as 270-300 m above sea level, discounting the marine features associated with the Pliocene formations. As many as four or five terraces are present along a few stretches of coast, but commonly there are only two or three. The lowest terrace extensively present along the coast has a shoreline angle of about 23-25 m above sea level, and the excellent preservation of its shoreline features suggests that it may correlate with the 30-m marine terrace at Santa Cruz and therefore probably be Sangamon in age. In a few places a terrace 6 or 12 m high can be identified below the 23-25-m terrace.

The broadest development of terraces is on the gently-sloping coast around Fort Bragg. Here flat-topped interfluves in a coastal belt about 8 km wide are benched by four to six broad marine terraces ranging from 12 to 180 m in altitude. Marine sands on these terraces range up to 15 m in thickness (California Dept. Water Resources, 1958, p. 85). This is a region of heavy winter rainfall, and it supports a forest of conifers, tan-oak, and rhododendron. The acid litter on these extremely flat, poorly drained terraces has led to strongly developed ground-water podzols (the Blacklock series) in which a chalk-white A-horizon 0.3-1 m thick consisting of pure silica silt overlies a thoroughly cemented ortstein B-horizon about 0.3-1 m thick, which rests directly on unweathered feldspathic beach sand (Gardner and Bradshaw, 1954). The vegetation, sealed off from soil nutrients by the ortstein, is now a pigmy forest, in which species normally 10-50 m tall form dense cane-like thickets less than 3 m high. The white A-horizons have given these terraces the name Mendocino White Plains.

The marine deposit covering the broad coastal flat at Crescent City has been named the Battery Formation (Maxson, 1933, p. 136; Back, 1937, p. 23). The shoreline angle of this marine terrace is about 30 m or less. According to Maxson the fauna of the Battery Formation resembles that of the Palos Verdes Sand (of presumably Sangamon age) in southern California.

Terrace deposits in the Eel River Lowland are predominantly fluvial, although they grade seaward into marine deposits. Ogle (1953) named the oldest Pleistocene terrace deposits the Hookton Formation and one of the younger the Rohnerville Formation. Both are deformed, the Hookton having dips as steep as 19° and the Rohnerville as steep as 5°. Ogle (1953) correlated the Hookton Formation with the 270 m terrace at False Cape and Cape Mendocino. This correlation requires at least 320 m of vertical deformation in the Eel River area (see Fig. 11). Inasmuch as the Carlotta Formation is early Pleistocene in age, this 320 m of deformation must have taken place in late-Pleistocene time.

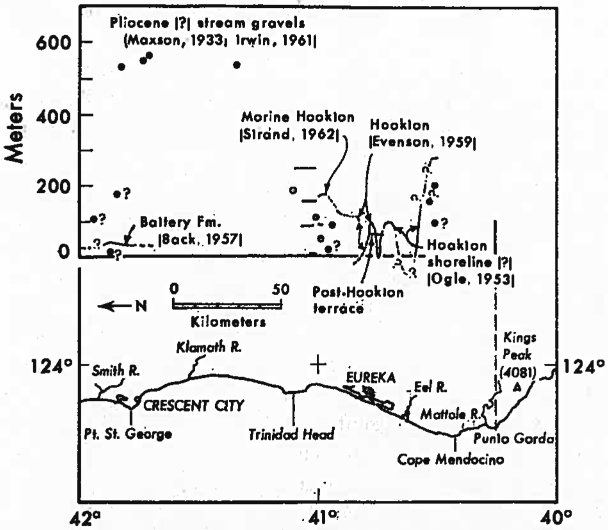

Figure 11. Marine terraces between Punta Gorda and the Oregon border, projected onto a north-south vertical plane. Compiled from topographic maps at 1:24,000 and 1:62,500 and from various sources. Height of Kings Peak is 1,244 m (4,081 ft).

The continental shelf off the northern Coast Ranges is a remarkably smooth plain that extends 8-24 km outward from the shore to the −180-m submarine contour at the top of the continental slope. Rocky bottom encountered on parts of this shelf suggests that much of it might be thinly mantled with sediment and that it might therefore be a wave-planed platform. Its remarkable smoothness contrasts strikingly with the abrupt coast, which rises 1,200 m in less than 5 km at one point a few kilometers southeast of Punta Gorda. The combination of smooth submarine platform, whose lower limit lies close to the level of Pleistocene low sea-level stands, with scattered terrace remnants along most of the coast and absence of any marine deposits younger than Pliocene inland, suggests that the shoreline has maintained a relatively constant geographic position during a steady rise of the land of as much as 300 m relative to sea level during the Quaternary, and that uplift and wave erosion have been very nearly in balance during this rise.

As elsewhere along the California coast, river-mouth estuaries and thick alluvial fill along the lower courses of large streams give ample evidence that sea level in Wisconsin time was a 100 m or more below present sea level. (Higgins, 1952, p. 240; Evenson, 1959, p. 19). Recent mineralogic studies of marine and beach sands south of the Russian River (Cherry, 1964; Minard, 1964) have shown that much of the sand on the shelf and beaches was transported southward from the mouth of the Russian River during the low sea-level stand along a shoreline several miles west of the present shore.

THE DRAINAGE PATTERN

Drainage in the Klamath Mountains and northern Coast Ranges has had the multiplicity of origins and complex history to be expected in an emergent mountain region of great tectonic instability. The longest-emergent region, the Klamath Mountains and adjacent northeastern part of the northern Coast Ranges, appears to have the oldest drainage (chiefly the Klamath River and its tributaries), which may have persisted essentially unchanged in pattern since early-Cenozoic time. Elsewhere, the oldest segments of drainage are headwater streams along high drainage divides that were probably islands in the Miocene and Pliocene seas. These areas have a drainage closely adjusted to the structure of the Franciscan bedrock. Successively younger increments of drainage were added as the sea withdrew to the south and west. Some of these are consequent segments formed as already existing drainage extended across newly emergent coastal plains; others are consequent streams along the troughs of newly emergent synclines or prograded lower courses in deltaically filled synclinal embayments. On the east side of the main drainage divide east-flowing consequent streams were incised into uplifted Plio-Pleistocene pediment gravels and superposed onto north-striking, steeply dipping sandstone and shale. Subsequent drainage changes reflect the effects of localized uplift or subsidence, or resulted from headward erosion and stream capture along belts of weak rock (for example, the north-flowing course of Stony Creek). A remarkable number of streams have been able to maintain their courses across uplifted belts and avoid defeat or capture, and other streams have not been captured although conditions seem appropriate for capture.

One of the most striking cases of supposedly imminent capture that may never occur is at the headwaters of the Mattole River and South Fork of the Eel, where the drainage divide for a distance of 27 km is between 1.5 and 3 km from the Pacific Ocean at an altitude of 330 to 800 m. In spite of the abrupt drop to the Pacific and the steepness of the ravines that score the mountain wall facing the ocean, there is relatively little evidence of eastward migration of this divide by stream capture. Most fingertip tributaries of the Mattole and Eel Rivers heading in this divide are markedly steeper than the larger streams into which they flow, and at only three or four places along the divide does an obviously underfit stream flow sluggishly eastward away from a wind gap.

The best-known example of a prograded and antecedent stream in the northern Coast Ranges is the Russian River. This stream flows southward through a linear system of structural valleys and intervening canyons for about 95 km into the north end of a plain that extends southeast toward San Pablo Bay (Fig. 9). It flows diagonally southward across this plain, and at its west side turns abruptly west to cross the southern end of the Mendocino Plateau in a narrow meandering gorge about 300 m deep. Lawson (1894, p. 269) and Weaver (1949, p. 167) thought that the Russian River originally flowed to San Pablo Bay and was deflected by crustal warping and drainage capture to a new course westward to the ocean. Higgins (1952) has effectively disproved this hypothesis and has shown that the Russian River originally emptied into the Merced embayment and prograded its course westward as the sea withdrew. According to Higgins, the plateau was uplifted after this marine withdrawal, and the river was able to maintain its course across the uplift by virtue of the volume of water and debris it was carrying. Lesser streams to the south were deflected by the uplift of the coastal belt, and their former headwaters now flow to the Russian River or to San Pablo Bay.

Cache Creek and Putah Creek are probably antecedent to the uplift of the Vaca Mountains. The headwaters of Cache Creek subsided to allow the accumulation of the Plio-Pleistocene Cache Beds and the formation of the alluviated basin of Clear Lake. Downstream, Cache Creek crosses the Cretaceous core of the Vaca Mountains in a narrow V-shaped gorge nearly 600 m deep. At the east end of this gorge it turns south to flow for 25 km through Capay Valley, a structural depression involving the late-Pliocene Tahama Formation. The course of Cache Creek along this valley is probably the consequence of the uplift of the Rumsey Hills to the east.

Subsidence is probably still going on at the headwaters of Cache Creek, for about 8 km northeast of Clear Lake is a narrow dendritic alluvial plain, Long Valley (not shown on Fig. 9), which lies in rugged mountains of mature dendritic topography. The dendritic pattern of this plain could have come about only through erosion. Alluvium beneath the center of the plain is at least 60 m thick (Upson and Kunkel, 1955), yet the stream exiting from Long Valley, a tributary of the North Fork of Cache Creek, flows on bedrock. The deep alluviation of the valley is presumably the result of tectonic sagging across the course of Long Valley Creek.

At the headwaters of Putah Creek are several interconnecting plains of irregular pattern, about 300 m above sea level, whose surfaces are interrupted by numerous bedrock hills. The aspect here is of a mature topography that has been alluvially drowned. Some of these plains have more than 45 m of alluvium, yet drainage from them flows for many kilometers on bedrock (Upson and Kunkel, 1955). Downstream from these headwater plains, Putah Creek crosses Berryessa Valley (now Lake Berryessa), a plain 5 km wide and 20 km long underlain by an unknown thickness of alluvium. Putah Creek leaves Berryessa Valley via a narrow V-shaped gorge through the Vaca Mountains similar to the gorge of Cache Creek.

GLACIATION

The Klamath Mountains were the site of numerous small cirque and valley glaciers during the Pleistocene ice advances, as well as a few ice carapaces on sloping mountain sides (Sharp, 1960), but they did not have an extensive ice sheet, and few glaciers extended across drainage divides. In the northwestern corner of the state, mountains as low as 1,700 m had glaciers on their north sides with cirque floors as low as 1,600 m; farther east in the interior parts of the Klamath Mountains, peaks 2,000-2,100 m high had glaciers on their north sides with cirque floors as low as 1,900-2,000 ft (Davis, 1958). Contours on the climatic firn limit, approximated by the lowest mountains bearing south-facing cirques, are shown on Figure 3. In the northwest this limit was 150 m higher than the orographic firn limit, and in the southern Trinity Alps it was 450 m higher. The divergence between climatic and orographic firn limits southeastward is probably related to the decreasing cloudiness in that direction.

Pleistocene glaciers (at least those of Wisconsin age) were generally less than 15 km long. Some exceptional glaciers descended to 750-900 m altitude (Sharp, 1960); Hershey (1904) reports a patch of ancient till 680 m in altitude in the western Klamath Mountains; however, most glacial termini of Wisconsin age are more than 1,200 m above sea level (Sharp, 1960). The distribution of Pleistocene glaciers recognizable from landforms on topographic maps is shown on Figure 3. Comparison with Sharp (1960) shows that these glaciers are Wisconsin in age, and correspond to the Tahoe and Tioga glaciations of the Sierra Nevada.

At the present time ,a few glacierets have a precarious existence at altitudes of 2,500-2,600 m on the sheltered north-facing sides of peaks 2,650-2,700 m high. Thus Wisconsin glaciation in the Klamath Mountains involved a lowering of firn limits by about 600 m.

A few high peaks of the eastern summit ridge of the northern Coast Ranges, all more than 2,100 m high, had tiny cirque and valley glaciers on their north-facing slopes (Davis, 1958). Their cirque floors have altitudes of 1,700 m. Lack of south-facing cirques makes estimation of a climatic firn limit difficult, but comparison with the Yolla Bolly Mountains and Trinity Alps suggests that it is about 2,400 m in altitude. Davis correlates the latest glaciation of the northern Coast Ranges with the Tahoe Glaciation of the Sierra Nevada.

The first study of glaciers in the Klamath Mountains was by Hershey (1900). He reported (Hershey, 1903a, b) evidence for three glacial advances in the Trinity Alps: an ancient advance, most of whose deposits were destroyed; an intermediate advance, of which boulders of granitic rocks in till are completely rotted to grus, and whose till itself (consisting largely of serpentine boulders) is oxidized to depths of 4.5-6 m; and a young advance, with unweathered till and unmodified glacial landforms. He correlated the intermediate advance with the Iowan (now early Wisconsin) and the young advance with the Wisconsin. At Orleans on the Klamath River he recognized (1903b, c, 1904) a total of six terraces ranging from 14 to 250 m above present river level. The three higher terraces (140, 205, and 250 m) have deep red soils, and the boulders in their gravels are thoroughly disintegrated. The 351- and 21-m terraces have reddish-brown soils, and the 14-m terrace an immature soil. He traced the 25-m terrace into tills of the intermediate glaciation, and he correlated the ancient glaciation with one of the higher terraces.

Maxson (1933) mentioned glaciation in the extreme northwestern part of the state, and Holway (1911) described glacial deposits and landforms in the northern Coast Ranges.

Recently Sharp (1960) recognized four and possibly five distinct glacial advances in the Trinity Alps. Moraines of his Morris Meadow (late-Wisconsin) substage are fresh with well-preserved topographic form, and diorite boulders projecting from the walls of cuts into these moraines ring to the blow of a hammer. Moraines of his Rush Creek (middle-Wisconsin) substage are fairly well preserved, and diorite boulders exposed in cuts are 90% projecting; many are still fresh enough to ring to the blow of a hammer, although some boulders have disintegrated rims surrounding solid cores. Moraines of his Alpine Lake (early-Wisconsin) substage are preserved as scattered remnants only, and 90-100% of the boulders in at least the upper 4.5-6 m of cutbanks are converted to grus. Brownish-red soils with ironstone pellets occur on tills of this substage. Pre-Wisconsin till was recognized on Swift Creek, a stream draining the eastern Trinity Alps; still older till, overlain by oxidized slopewash with a deep-red soil 3 m thick and oxidized to a thickness of 20 m, was found on Canyon Creek, a tributary of the Trinity River draining the southwest part of the Trinity Alps. He found the Wisconsin tills to correlate with terraces 3, 12, and 18 m above Canyon Creek; he correlated his younger pre-Wisconsin till with a 27-m terrace and his older pre-Wisconsin till with a 90-m terrace on the same creek.

Presumably Sharp's three Wisconsin tills correspond to Hershey's younger glaciation, his late-pre-Wisconsin till to Hershey's intermediate glaciation, and his early pre-Wisconsin till to Hershey's old glaciation. Sharp does not discuss Hershey's localities, so presumably Hershey's exposures were no longer available when Sharp made his study. Sharp's description of his tills suggests that the three youngest correlate with the Tioga, Tenaya, and Tahoe Glaciations of the Sierra Nevada.

The Quaternary of Southern California

INTRODUCTION

One of the thickest marine Quaternary sections in the world is in the Ventura and Los Angeles Basins of southern California. As much as 1,500-1,850 m of fossiliferous marine lower Pleistocene sediments are moderately to intensely deformed and are overlain unconformably by marine terrace deposits on as many as 13 terraces ranging up to 450 m above sea level. The marine lower Pleistocene is the youngest part of the thick, largely terrigenous petroliferous sedimentary succession in these basins, a succession that ranges in age from Upper Cretaceous to Pleistocene and totals 15,000 m in thickness. The marine Quaternary sediments interfinger northward and eastward with continental deposits derived from the Transverse Ranges.

The remarkable deformation of the lower-Pleistocene sediments and the unconformity between them and the upper-Pleistocene terrace deposits have led many geologists (Eaton, 1928; Reed, 1933; Reed and Hollister, 1936; Bailey, 1943) to conclude that the major orogeny since mid-Cretaceous time in Southern California was in the mid-Pleistocene. However, the enormously thick terrigenous Miocene and Pliocene section in these basins and the abundance of coarse clastic rocks, particularly in the continental facies, suggest that uplift of the adjacent mountain masses must have been relatively continuous throughout much of the late Cenozoic; the deformation may appear to be more intense in the Quaternary because the locus of deformation reached the central parts of the basins then, and possibly also because the older angular unconformities, which may have been localized around the margins of the earlier basins, somewhat larger than the present basins, were destroyed during continued uplift and erosion.

Limitations of space make only a brief summary of the

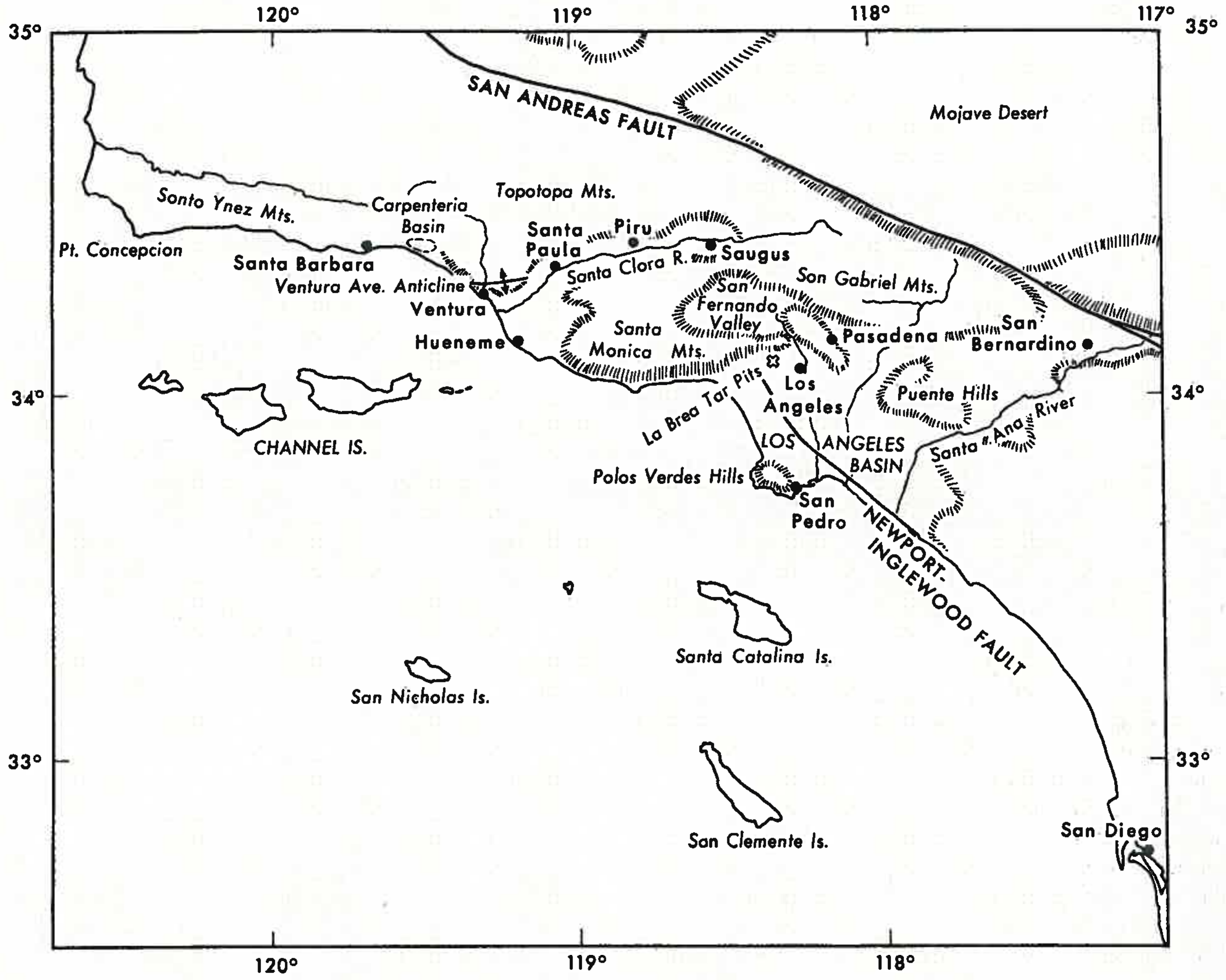

Figure 12. Map of southern California, showing localities mentioned in text.

Southern California Quaternary possible. The geologic framework of Southern California is covered in Jahns (1956), especially in Chapter 2 of that bulletin. The modern environment of marine sedimentation is treated at length in the excellent work of Emery (1960). Localities mentioned in the text are shown in Figure 12.

THE LOWER PLEISTOCENE OF THE VENTURA BASIN

The marine lower Pleistocene of the Ventura Basin is generally mapped as two formations, the Santa Barbara and the San Pedro. These rocks are exposed mainly in the western part of the basin, west of the longitude of Santa Paula, and grade eastward into the continental Saugus Formation. Locally, all formations are overlain unconformably by younger deformed continental gravels and marine terrace deposits.

The type locality of the Santa Barbara Formation is on the west side of Santa Barbara, where it is about 600 m of siltstone and fine sandstone with one conspicuous bryzoal reef bed (Upson, 1951a). It is considered by some authors (Bailey, 1935, 1943; Bailey and Jahns, 1954) to range from upper Pliocene to lower Pleistocene, and by others (Woodring *et al.*, 1940; Woodring, 1952; Upson, 1951a) to be entirely Pleistocene. In the Ventura area, the beds mapped as Santa Barbara by Bailey (1935, 1943) consist of 650 m of silty shale and mudstone with discontinuous lenses of conglomerate and correspond to the Upper Pico as mapped by Kew (1924) and Putnam (1942). Southward toward Oxnard, the Santa Barbara thins to 60-90 m of sandstone (Thomas *et al.*, 1954).

The Santa Barbara in the Ventura area is overlain conformably by 600 m of sand and silt and 300 m of poorly consolidated gravel, correlated by Bailey (1943) with the San Pedro Formation, a usage that has been followed by Thomas *et al.* (1954) and by Page (1963). The San Pedro of Bailey corresponds to the marine Saugus of Kew (1924). It also thins southward from 900 m north of the Santa Clara River to 250 m near Hueneme.

In the Carpenteria Basin between Santa Barbara and Ventura the Santa Barbara Formation is unconformably overlain by 1,200 m of folded red continental gravel, the Casitas Formation (Upson, 1951a). At the east end of the Ventura Basin, around Saugus and at the north edge of the San Fernando Valley, the deformed continental Quaternary rocks include the Saugus Formation, 900-2,000 m of coarse conglomerate and sandstone derived from mountains to the east and north, and the Pacoima Formation, 150-300 m of extremely coarse conglomerate and breccia, which overlies the Saugus with marked angular unconformity (Winterer and Durham, 1962; Oakeshott, 1958). At its base the Saugus interfingers with marine upper Pliocene rocks and therefore corresponds to the marine Quaternary succession farther west. In the area between Ventura and Santa Paula, Bailey (1935) mapped interfingering relationships between the marine and continental formations.

The lower Pleistocene formations are folded and faulted. At its type locality the Santa Barbara Formation dips 25° SE. Farther east, at the east end of the Carpenteria Basin, it dips 59°, and the unconformably overlying Casitas Formation dips as much as 45° (Upson, 1951a). In the Ventura area, the Quaternary formations are folded along with the Pliocene into the Ventura Avenue anticline, whose flanks dip 35°-45°, and southerly dips increase eastward until in the vicinity of Santa Paula the beds are overturned. The most intense deformation is between Santa Paula and Piru, where the beds are caught in a tight syncline whose axis is the present Santa Clara River valley, overturned on both limbs, and overthrust from both north and south by older Tertiary rocks (Kew, 1924; Bailey and Jahns, 1954; Bailey, 1954; see King, this volume, Fig. 15, for a structure section). At the extreme east end of the Ventura Basin the continental formations in San Fernando Valley have been overthrust by the crystalline rocks of the San Gabriel Mountains. Structural relief here exceeds 4,500 m (Oakeshott, 1958; Winterer and Durham, 1962).

THE LOWER PLEISTOCENE OF THE LOS ANGELES BASIN

The classic area for the Southern California Quaternary is around the seaport of San Pedro and the adjacent Palos Verdes Hills. The abundant marine Pleistocene fauna was described in a classic monograph by Ralph Arnold (1903). The fossiliferous strata were later studied by Crickmay (1929), Grant and Gale (1931), and most recently by Woodring *et al.* (1946), Valentine (1961), and Valentine and Meade (1961). Woodring *et al.* divided the deposits into four formations: the Lomita Marl, Timms Point Silt, San Pedro Sand, and Palos Verdes Sand. The first three formations are all lower Pleistocene and locally dip 12°-35°; the Lomita Marl and Timms Point Silt are local facies, and grade laterally into the basal San Pedro Sand. The Palos Verdes Sand (equivalent to the Upper San Pedro of Arnold, 1903) is the marine cover on the youngest terrace, 23-45 m high, and was deposited across the bevelled edges of the older formations.

The Lomita Marl is a calcareous sand, 23-85 m thick, consisting largely of organic remains; it is present only along the eastern (lee) side of the Palos Verdes Hills. Its fossils suggest that it accumulated at a depth of 45-180 m, probably as a drifted accumulation of organic carbonate fragments, much as similar deposits accumulate today in the lee of Santa Catalina Island (Emery, 1960, p. 208-214). The Timms Point Silt is 10-33 m of brownish massive sandy silt whose contained fossils suggest accumulation in 90-180 m of water. The San Pedro Sand is 53-90 m of sand and gravel whose fossils suggest a shallow-water environment, generally less than 20 m (Woodring *et al.*, 1946). Although the presence of northern forms in the faunas from these lower Pleistocene formations led earlier workers to assign them to one of the early-Pleistocene glacial periods, Woodring *et al.* concluded that the influence of depth on fossil assemblages makes climatic comparisons dangerous. Emiliani and Epstein (1953) likewise regarded low temperatures determined from oxygen-isotope ratios as the effect of oceanic currents and coastal upwelling as much as of world-wide climatic fluctuations.

The deformed Quaternary succession is the thin western edge of the sediments that lap against the Palos Verdes Hills, which were probably an island in the early-Quaternary sea. These sediments thicken northeastward to 900 m beneath the center of the Los Angeles Basin, where they rest conformably on marine Upper Pliocene rocks (Woodford *et al.*, 1954). Presumably the marine section in the center of the basin interfingers eastward with continental gravels exposed along the border of the Puente Hills, for example the La Habra Formation (Durham and Yerkes, 1964). North and east of the Puente Hills, 100-600 m of coarse continental gravels underlie the alluvial plain between Pasadena and San Bernardino (Dutcher and Garrett, 1963).

MARINE TERRACES AND THE LATE QUATERNARY

The marine terraces of Southern California were first described in detail by Lawson (1893b) and have been summarized by Emery (1960). Upson (1951b) found well-defined terraces at 18, 27, 38, and 60 m on the coast west of Santa Barbara and inferred sea-level stands there as high as 500 m on the basis of level ridge crests. Davis (1933) recognized three marine terraces whose height increased eastward along the coast of the Santa Monica Mountains. Ellis and Lee (1919) recognized five terraces near San Diego, at altitudes of 6, 15, 30, 75, and 150 m, and noted that the terraces are slightly deformed and increase in altitude southward across the border with Mexico.

Terraces occur on several of the Santa Barbara Islands. On Santa Rosa Island, Orr (1960) recognized seven marine terraces, of which the lowest three, 7.5, 23, and 30 m, are probably of Wisconsin age. On San Clemente Island, Lawson (1893b) and W. S. T. Smith (see Olmsted, 1958) recognized 20 marine terraces, the highest about 450 m above sea level.

Nine marine terraces were recognized by Putnam (1942) in the mountains between Ventura and the Carpenteria Basin, ranging in altitude up to 400 m. All of these, including the lowest, slope westward parallel to the coast at 20 m/km. The 60-m terrace merges with a stream terrace on the Ventura River that is upwarped 120 m within a span of 9 km by late-Pleistocene movement on the Ventura Avenue anticline. East of Ventura, fanglomerates containing an upper Pleistocene fauna dip 8°-20° south off the flank of this anticline and rest on the San Pedro Formation with angular unconformity of 25°-30° (Bailey, 1943, see King, this volume, Fig. 15, for a cross-section).

Woodring *et al.* (1946) recognized 13 marine terraces in the Palos Verdes Hills, the highest at 400 m above sea level (see King, this volume, Fig. 20, for sections). Fossiliferous marine deposits were found as high as the 12th terrace. They thought that all these terraces were cut after the lower-Pleistocene formations were folded; however, the shallow depth of accumulation of the lower-Pleistocene formations, and their distribution around the base of the hills, make it possible for some of the highest terraces to be contemporaneous with the lower-Pleistocene succession.

The Palos Verdes Sand rests on the lowest marine terrace, and both are widely distributed in the western part of the Los Angeles basin and are locally deformed. Along the northeastern margin of the Palos Verdes Hills they are warped into a monocline with about 120 m of displacement (Woodring *et al.*, 1946). Along the Newport-Inglewood fault zone the Palos Verdes Sand dips as much as 3° on the flanks of broad faulted anticlines where it has been differentially uplifted as much as 120 m (Poland, Piper *et al.*, 1956; Poland *et al.*, 1959). These structures are little eroded and are faithfully recorded in the present topography. They represent renewed or continuing movement on major oil-field anticlines in the Los Angeles Basin, on whose flanks the buried upper Pliocene beds dip 30°-45° (Driver, 1943; Grinsfelder, 1943; Stoltz, 1943; Weaver and Wilhelm, 1943).

The marine fauna of the Palos Verdes Sand and lowest marine terrace, which presumably lived during the Sangamon interglacial, has many cold-water forms of more northern distribution at present where the terrace deposits are in exposed positions; where the terrace deposits represent sheltered shallow-water embayments, warm-water forms of more southern present distribution are found. Valentine (1961; see also Valentine and Meade, 1961) interprets this to be caused by more intense upwelling than at present, which brought cold water to the surface along exposed coasts, while the shallow water of the embayments was warmed by contact with the warmer interglacial atmosphere.

As Durham (1954) points out, there are no deposits or landforms on the inner margins of the Los Angeles or Ventura Basins to correspond to the marine-terrace deposits on the exposed coastline and the offshore islands.

Little-deformed alluvial deposits around the inner margin of the Los Angeles basin may be contemporaneous with or slightly younger than the Palos Verdes Sand. In these deposits are the famous La Brea tar pits, which have produced an enormous abundance of late-Pleistocene vertebrate remains, including *Canis*, *Smilodon*, *Camelops*, *Bison*, *Equus*, *Mylodon*, *Nothrotherium*, *Mammut*, and *Archidiskodon* (Stock, 1930). These pits are the type locality for the upper Pleistocene Rancholabrean land-mammal age.

The Wisconsin low sea-level stand is recorded in the Los Angeles Basin by filled gorges of the Santa Ana, San Gabriel, and Los Angeles Rivers, whose floors were as much as 55 m below the present plain (Poland, Piper *et al.*, 1956; Poland *et al.*, 1959). As sea level rose these gorges were filled by a lower unit of coarse gravel and an upper unit of fine sand and silt.

GLACIATION

Evidence of seven valley glaciers on the north slope of the highest ridge of the San Bernardino Mountains has been reported by Sharp *et al.* (1959). The glaciers accumulated at altitudes of 3,100-3,400 m on the north flanks of mountains 3,200-3,500 m high and descended distances of 0.8-2.7 km to altitudes of 2,650 m or higher. Till tentatively correlated with both the Tioga and Tahoe advances of the Sierra Nevada has been recognized, but no older glacial deposits. San Jacinto Peak (3175 m) may have had a glacier on its northeast side, although the evidence is doubtful. The San Gabriel Mountains (maximum altitude 3,075 m) do not appear to have been glaciated, contrary to earlier reports.

CONCLUSIONS

The Quaternary history of California is characterized not only by climatic change, but also by widespread tectonism and volcanism. The thick Quaternary deposits are ultimately the result of tectonic activity. So impressive is the evidence for tectonism that the view has been widely held that California was affected by a mid-Pleistocene orogeny that was more intense than any since mid-Cretaceous—the Pasadenan orogeny of Stille (see King, this volume). More recent evidence does not support this view; rather, Quaternary tectonic activity in California appears to be a continuation of orogenic activity that proceeded with varying intensity since at least the middle Miocene.

The character of the deformation varies from place to place depending on (1) the character of the basement rock and (2) the physiographic province. Areas underlain by granitic batholiths and crystalline metamorphic rocks—together called Sierran basement—are characteristically broken into blocks tens of kilometers wide and hundreds of kilometers long that were tilted and displaced relative to each other but were not significantly deformed internally. Examples are the westward-tilted fault blocks of the Sierra Nevada, Peninsular Range, and Gabilan Range. Areas underlain by the thick, slightly metamorphosed eugeosynclinal succession known as the Franciscan Formation are characteristically deformed into complex folds. Examples are common in the Diablo and Santa Lucia Ranges and in the northern Coast Ranges. Sierran basement may also be intensely deformed and may appear in the cores of fairly tight folds where it is close to major strike-slip or thrust faults, as in the Santa Cruz and Santa Lucia Mountains, or overlain by a thick sedimentary succession, as in parts of the Transverse Ranges.

Geographically deformation varies from apparent crustal extension east of the Sierra Nevada to apparent crustal shortening and large right-lateral displacement near the Pacific Coast. The normal faults that produced much of the eastern front of the Sierra Nevada and are common throughout the Great Basin to the east represent crustal extension. The Sierra Nevada itself, together with the eastern two-thirds of the Great Valley, was—except at its southern end—tilted more or less as a unit. It is now 2,500-4,700 m high along its eastern crest, and the basement descends to depths greater than 6,000 m along the valley axis.

The Coast Ranges have local areas of relatively intense folding, some overthrusting along northwest-trending structures, and numerous right-lateral faults of large displacement. Current displacement on the San Andreas Fault, the largest strike-slip fault, takes place at the rate of 5 cm per year, and it supports the largest estimates of displacement along this fault since the Cretaceous or early Tertiary. The

Transverse Ranges are tightly deformed with westerly structural trends; crustal shortening seems to be involved in such structures as the Santa Clara River Valley syncline.

Quaternary volcanic rocks are widely distributed throughout California. Quaternary volcanism, like tectonic activity, is a continuation of processes that persisted throughout the later Cenozoic. Volcanism continued into the Recent; there have been two eruptions within the state in the last 150 years, radiocarbon dates indicate that several more have occurred within the last millennium, and hot springs and solfataras are common in the volcanic regions. Chief centers of Quaternary volcanic activity are the Cascade Range, Modoc Plateau, the eastern side of the Sierra Nevada—notably near Truckee, Mono Lake, Big Pine, and at the headwaters of the south fork of the Kern—the Sutter Buttes in Sacramento Valley, and the Clear Lake area in the northern Coast Ranges.

Volcanic rocks dated by the potassium-argon method show that volcanism has been persistent throughout the Quaternary. However, eruptions were particularly widespread about 3-3.5 million years ago, near the beginning of the Quaternary. The dated volcanic rocks help establish the absolute ages of the fossiliferous sediments, glacial deposits, erosion surfaces, and tectonic phenomena with which they are associated.

Sediments eroded from the Quaternary uplifts, or from mountains already in existence at the end of Pliocene time, accumulated in subsiding basins. The largest basin is the Great Valley, and the upper 700-1,500 m of the sedimentary succession in its southern half is of Quaternary age. Bordering most of the structural lowlands within the Coast Ranges and in Southern California, and buried beneath younger sediments on the floors of the structural valleys, are deformed bodies of sedimentary rocks commonly a few hundred to 1,500 m thick that range in age from uppermost Pliocene through lower and perhaps middle Pleistocene. Throughout the entire northern Coast Ranges and most of the southern Coast Ranges these deformed Plio-Pleistocene formations rest unconformably on older rocks, including tightly folded rocks of middle-Pliocene age; on the other hand, in the oil-field regions of the southern San Joaquin Valley and the basins of southern California, these beds rest conformably on the marine Pliocene, and they gave most geologists working there the impression that Cenozoic deformation prior to the middle Pleistocene had been minor. The deformed Plio-Pleistocene sediments unconformably underlie relatively undeformed alluvial, lacustrine, estuarine, and eolian deposits as much as a few hundred meters thick.

Most of the Plio-Pleistocene and late-Quaternary sediments are continental in origin and contain scattered vertebrate fossils, freshwater mollusks, and diatoms. The type Irvingtonian (middle-Pleistocene) and Rancholabrean (upper-Pleistocene) faunas of the North American land-mammal ages are from localities within California. Radiometric dates from California have shown that the late-Pliocene lower-Blancan faunas (in the sense of Hibbard *et al.*, this volume) are about 3.4 million years old and that a fauna that is either Irvingtonian or Rancholabrean is 600,000 years old.

Along the coast, marine formations contain abundant invertebrate fossil assemblages. Ties with the European and Atlantic faunas have not yet been securely established, and the ages of the marine formations have been based on percentage of extinct marine forms, presence of cold-water forms, and correlation with formations having vertebrate-fossil control.

The marked climatic fluctuations during the Quaternary are represented in California by glacial deposits and landforms, marine terraces, cut-and-fill relations in alluvium, and pluvial lake cycles. (For a discussion of pluvial cycles see the article by Morrison, this volume.) During the latest glaciations the Sierra Nevada supported a mountain ice cap 450 km long and 50 km wide, mountain glaciers were common in the Cascade Range and Klamath Mountains, and a few cirque glaciers were present on high peaks of the northern Coast Ranges and of the San Bernardino Mountains in southern California. Climatic firn limit ranged from 2,000 m in the northwest corner of the state to 4,000 m near Mt. Whitney, and firn limits in general were about 600-750 m lower than at present.

The classic glacial sequence in California is in the eastern Sierra Nevada, where the following Pleistocene glaciations have been established: McGee, Sherwin, Mono Basin, Tahoe, Tenaya, Tioga. The last three are correlated with the Wisconsin of the mid-Continental United States (see Morrison, this volume). Tahoe till apparently overlies basalt dated at less than 100,000 years. The Mono Basin is younger than, and the Sherwin older than, the Bishop Tuff, dated at 700,000 years. McGee till, which is apparently older than Sherwin, rests on basalt 2.3 million years old.

Marine terraces and associated deposits are common along the California coast. As many as 20 terraces have been found in a single flight, the highest at 450 m. Terraces 400 m high transect deformed early-Pleistocene formations. The terraces are moderately deformed so that their shoreline angles slope a few tens of meters per kilometer. Locally they may be tilted a few degrees. The lowest persistent terrace is about 30 m above sea level and has been dated by the U-Th methods at about 115,000 years. In Southern California deposits on this terrace have a cold-water fauna on exposed coasts and a warm-water fauna in protected shallow embayments, suggesting that upwelling and oceanic currents may have as much of an effect on marine climate as air temperature. The type Rancholabrean fauna may be in deposits contemporaneous with or slightly younger than the lowest marine terrace. Following the cutting of the lowest marine terrace, sea level fell at least 100 m below its present level. The subsequent postglacial sea-level rise accounts for San Francisco Bay and other drowned river mouths.

The marine terraces present two problems as yet unsolved: (1) There are no deposits or landforms in the interior valleys of California to correspond with the high sea-level stand that the terraces represent. (2) The marine terraces transect continental Plio-Pleistocene formations at many places, a relationship that implies that the entire marine-terrace sequence represents a sea-level rise (relative to California) following a fairly low sea-level stand in early-Pleistocene time. Since this sequence of events has not been reported elsewhere, it may result from tectonic conditions along the California coast.

Fossiliferous sediments as well as dated volcanic rocks and marine terraces have made possible estimates of the progress of tectonic activity in various parts of California during the Quaternary. Volcanic rocks within a few hundred feet of the bottoms of gorges cut into the western slope of the Sierra Nevada indicate that the bulk of the uplift and tilting occurred more than 3.5 million years ago. On the other hand, as much as 1,000 m of displacement may have taken place on the eastern escarpment since the deposition of the McGee till, less than 2.3 million years old. Locally a few hundred meters of more of this displacement took place since the eruption of the Bishop Tuff, 700,000 years ago; moraines of Tahoe and Tioga glaciations are locally offset several meters. Inasmuch as the isotopically dated volcanics and the ancient glacial deposits indicate that the Sierra Nevada was about as high at the beginning of the Pleistocene as it is now, the Quaternary displacement along the eastern boundary escarpment may represent foundering of the Owens Valley block. The amount and time of Quaternary displacement varied greatly from place to place along the escarpment.

In the Coast Ranges a major period of uplift and erosion preceded the accumulation of the Plio-Pleistocene formations; these formations were in turn deformed, at least around the margins of the intermontane basins, once or more during the Pleistocene. Near San Francisco Bay most of this deformation seems to have taken place between Irvingtonian and Rancholabrean time. On the east side of the Diablo Range sharp monoclinal flexuring and broad folding took place less than 600,000 years ago.

Even the youngest marine terraces are locally deformed, indicating significant crustal warping in the last 100,000 years. Along the Newport-Inglewood Fault in the Los Angeles Basin, deposits of the youngest terrace dip 3° off the flanks of folds with 120 m of closure; the buried uppermost Pliocene beds in these same folds have dips of 30°-45°, suggesting that deformation has been relatively continuous throughout the Quaternary. Tectonic activity continues unabated, for California has a major earthquake about once a decade (VanderHoof, 1955; Tocher, 1959).

References

Alexander, C. S., 1953, The marine and stream terraces of the Capitola-Watsonville area: Univ. California Publ. Geogr., v. 10, p. 1-44

Anderson, C. A., 1936a, Volcanic history of the Clear Lake area, California: Geol. Soc. Amer. Bull., v. 47, p. 629-644

—— 1936b, The Tuscan Formation of northern California, with a discussion concerning the origin of volcanic breccias: Univ. California Publ. Geol. Sci., v. 23, p. 215-275

—— 1941, Volcanoes of the Medicine Lake Highlands, California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 25, p. 347-422

Anderson, C. A., and Russell, R. D., 1939, Tertiary formations of northern Sacramento Valley, California: California J. Mines Geol. (State Mineralogist's Rep.), v. 35, p. 219-253

Anderson, Robert, and Pack, R. W., 1915, Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, California: U.S. Geol. Surv. Bull. 603, 220 p.

Arkley, R. J., 1962a, The geology, geomorphology, and soils of the San Joaquin Valley in the vicinity of the Merced River, California: California Div. Mines Geol., Bull. 182, p. 25-31

—— 1962b, Soil Survey of the Merced area, California: U.S. Dept. Agric., Soil Cons. Serv., Soil Surv., Ser. 1950, No. 7, 131 p.

Arnold, Ralph, 1903, The paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, California: California Acad. Sci. Mem., v. 3, 420 p.

Arnold, Ralph, and Anderson, Robert, 1910, Geology and oil resources of the Coalinga District, California, with a report on the chemical and physical properties of the oils by Irving C. Allen: U.S. Geol. Surv. Bull. 398, 272 p.

Arnold, Ralph, and Johnson, H. R., 1910, Preliminary report on the McKittrick-Sunset oil region, Kern and San Luis Obispo Counties, California: U.S. Geol. Surv. Bull. 406, 225 p.

Ashley, G. H., 1895, The Neocene stratigraphy of the Santa Cruz Mountains of California: California Acad. Sci. Proc., 2nd ser., v. 5, pt. 1, p. 273-367

Averill, C. V., 1937, Mineral resources of Plumas County: California J. Mines Geol. (State Mineralogist's Rep.), v. 33, p. 79-143

Axelrod, D. I., 1944, Pliocene floras of California and Oregon—the Sonoma Flora: Carnegie Instn. Publ. 553, p. 162-206

—— 1957, Late Tertiary floras and the Sierra Nevadan uplift: Geol. Soc. Amer. Bull., v. 68, p. 19-46

—— 1962, Post-Pliocene uplift of the Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 73, p. 183-197

Axelrod, D. I., and Ting, W. S., 1961, Early Pleistocene floras from the Chagoopa Surface, southern Sierra Nevada: Univ. California Publ. Geol. Sci., v. 39, p. 119-194

Back, William, 1957, Geology and ground-water features of the Smith River plain, Del Norte County, California: U.S. Geol. Surv. Water-Supply Pap. 1254, 76 p.

Bailey, Edgar H., Irwin, William P., and Jones, David L., 1964, Franciscan and related rocks, and their significance in the geology of western California: California Div. Mines Geol. Bull. 183, 177 p.

Bailey, T. L., 1935, Lateral change of fauna in the Lower Pleistocene: Geol. Soc. Amer. Bull., v. 46, p. 489-502

—— 1943, Late Pleistocene Coast Range orogenesis in southern California: Geol. Soc. Amer. Bull., v. 54, p. 1549-1568

—— 1954, Geology of the western Ventura Basin, Santa Barbara, Ventura, and Los Angeles Counties: *in* Jahns, 1954, map sheet 4

Bailey, T. L., and Jahns, R. H., 1954, Geology of the Transverse Range Province, southern California: *in* Jahns, 1954, Ch. 2, p. 83-106

Barbat, W. F., and Galloway, John, 1934, San Joaquin Clay, California: Amer. Assoc. Petroleum Geologists Bull., v. 18, p. 476-499

Bateman, Paul C., 1956, Economic Geology of the Bishop Tungsten District, California: California Division of Mines Special Report 47, 87 p

—— 1962, Geology, p. 100-122 *in* Schumacher, G. (ed.), Deepest valley: San Francisco, Sierra Club, 206 p.

—— in press, Geology and tungsten mineralization of the Bishop District, California: U.S. Geol. Surv. Prof. Pap. 470

Bauer, Francis H., 1952, Marine terraces between Salmon Creek and Stewart's Point, California: Berkeley, Univ. California M.A. thesis, 273 p.

Birkeland, Peter W., 1963, Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California: Geol. Soc. Amer. Bull., v. 74, p. 1453-1464

—— 1964, Pleistocene glaciation of the northern Sierra Nevada north of Lake Tahoe, California: J. Geol., v. 72, p. 810-825

Birman, J. H., 1954, Pleistocene glaciation in the upper San Joaquin basin, Sierra Nevada: *in* Jahns, 1954, Ch. 5, p. 41-44

—— 1957, Glacial geology of the upper San Joaquin drainage, Sierra Nevada, California: Los Angeles, Univ. California Ph.D. thesis, 237 p.

—— 1964, Glacial geology across the crest of the Sierra Nevada: Geol. Soc. Amer. Spec. Pap. 75, 80 p.

Blackwelder, Eliot, 1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geol. Soc. Amer. Bull., v. 42, p. 865-922

—— 1932, Glacial and associated stream deposits of the Sierra Nevada: Mining in California (State Mineralogist's Rep.), v. 28, p. 303-310

Blanchard, R. L., 1963, Uranium decay series disequilibrium in age determination of marine calcium carbonates: St. Louis, Washington Univ. Ph.D. thesis, 164 p.

Bowen, Oliver E., Jr. (ed.), 1962, Geologic guide to the gas and oil fields of northern California: California Div. Mines Geol. Bull. 181, 407 p.

Bradley, William C., 1956, Carbon-14 date for a marine terrace at Santa Cruz, California: Geol. Soc. Amer. Bull., v. 67, p. 675-678

—— 1957, Origin of marine-terrace deposits in the Santa Cruz Area, California: Geol. Soc. Amer. Bull., v. 68, p. 421-444

Branner, J. C., Newsom, F. S., and Arnold, Ralph, 1909, Description of the Santa Cruz area: U.S. Geol. Surv., Geol. Atlas of the United States, Folio 163

Brice, James C., 1953, Geology of Lower Lake quadrangle, California: California Div. Mines Bull. 166, 72 p.

Briggs, Louis I., 1953, Geology of the Ortigalita Peak quadrangle, California: California Div. Mines Bull. 167, 61 p.

Bryan, Kirk, 1923, Geology and ground-water resources of Sacramento Valley, California: U.S. Geol. Surv. Water-Supply Pap. 495, 285 p.

Büdel, Julius, 1957, Die "Doppelten Einebnungsflächen" in den feuchten Tropen: Z. Geomorph., v. 1, No. 2, p. 201-228

Bull, William B., 1964a, History and causes of channel trenching in western Fresno County, California: Amer. J. Sci., v. 262, p. 249-258

—— 1964b, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Surv. Prof. Pap. 437-A, 71 p.

California Department of Water Resources, Division of Resources Planning, 1958, Recommended water well construction and sealing standards, Mendocino County: *Their* Bull. 62, 169 + 60 p.

California State Water Resources Board, 1955, Santa Clara County investigation: *Their* Bull. 7, 153 p. (see p. 99-105)

Cardwell, G. T., 1958, Geology and ground-water in the Santa Rosa and Petaluma Valley areas, Sonoma County, California: U.S. Geol. Surv. Water-Supply Pap. 1427, 273 p.

Cater, Fred W., Jr., and Wells, Francis G., 1953, Geology and mineral resources of the Gasquet quadrangle, California-Oregon: U.S. Geol. Surv. Bull. 995-C, p. 79-133

Cherry, John, 1964, Sand movement along a portion of the northern California coast: Univ. California Hydraulic Engineering Lab., Tech. Rep. HEL—4-3, 150 p.

Christensen, M. N., in press a, Late Cenozoic deformation in the Central Coast Ranges of California: Geol. Soc. Amer. Bull.

—— in press b, Late Cenozoic movements of the earth's crust—Sierra Nevada of California: Geol. Soc. Amer. Bull.

Church, H. Victor, Jr., Krammes, Kenneth, *et al.*, 1957a, Cenozoic correlation section across south San Joaquin Valley from San Andreas Fault to Sierra Nevada foothills: Amer. Assoc. Petroleum Geologists, Pacific Sect., Correlation Sect. No. 8

—— 1957b, Correlation section across central San Joaquin Valley from San Andreas Fault to Sierra Nevada foothills: Amer. Assoc. Petroleum Geologists, Pacific Sect., Correlation Sect. No. 9

Clark, Samuel G., 1940, Geology of the Covelo District, Mendocino County, California: Univ. California Publ. Dept. Geol. Sci. Bull., v. 25, p. 119-142

Cohee, George V., *et al.*, 1961, Tectonic map of the United States, exclusive of Hawaii and Alaska (1:2,500,000): U.S. Geol. Surv. and Amer. Assoc. Petroleum Geologists

Colby, W. E., 1950, John Muir's studies in the Sierra: San Francisco, The Sierra Club, 103 p.

Cox, Allan, Doell, Richard R., and Dalrymple, G. Brent, this volume, Quaternary paleomagnetic stratigraphy

Crickmay, C. H., 1929, The anomalous stratigraphy of Deadman's Island, California: J. Geol., v. 37, p. 617-638

Crittenden, Max D., Jr., 1951, Geology of the San Jose–Mount Hamilton area, California: California Div. Mines Bull. 157, 74 p.

Crowell, John C., 1962, Displacement along the San Andreas Fault, California: Geol. Soc. Amer. Spec. Pap. 71, 61 p.

Cummings, J. C., Touring, R. M., and Brabb, E. E., 1962, Geology of the northern Santa Cruz Mountains, California: *in* Bowen, 1962, p. 179-220

Curtis, Garniss H., 1951, The geology of the Topaz Lake quadrangle and the eastern half of the Ebbetts Pass quadrangle: Berkeley, Univ. California Ph.D. thesis

—— 1954, Mode of origin of pyroclastic debris in the Mehrten formation of the Sierra Nevada: Univ. California Publ. Geol. Sci., v. 29, p. 453-502

Curtis, G. H., Evernden, J. F., and Lipson, J., 1958, Age determination of some granitic rocks in California by the potassium-argon method: California Div. Mines Spec. Rep. 54, 16 p.

Dale, R. F., 1959, Climates of the states; California: U.S. Dept. Commerce, Weather Bureau, Publ. 60-4 (Climatology of the United States) 37 p.

Dalrymple, G. Brent, 1963, Potassium-argon dates of some Cenozoic volcanic rocks of the Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 74, p. 379-390

—— 1964a, Cenozoic chronology of the Sierra Nevada, California: Univ. California Publ. Geol. Sci., v. 47, 41 p.

—— 1964b, Potassium-argon dates of three Pleistocene interglacial basalt flows from the Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 75, p. 753-757

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geol. Surv. Water-Supply Pap. 1469, 287 p.

Davis, Stanley N., 1958, Glaciated peaks in the northern Coast Ranges, California: Amer. J. Sci., v. 256, p. 620-629

Davis, Stanley N., and Hall, Francis R., 1959, Water quality of eastern Stanislaus and northern Merced Counties, California: Stanford Univ. Publ. Geol. Sci., v. 6, No. 1, p. 1-112

Davis, W. M., 1933, Glacial epochs of the Santa Monica Mountains, California: Geol. Soc. Amer. Bull., v. 44, p. 1041-1133

Dibblee, T. W., Jr., 1950, Geology of southwestern Santa Barbara County, California: California Div. Mines Bull. 150, 95 p.

—— 1958, Tertiary stratigraphic units of the western Mojave Desert, California: Amer. Assoc. Petroleum Geologists Bull., v. 42, No. 1, p. 135-144

—— 1962, Displacements on the San Andreas Rift Zone and related structures in Carrizo Plain and vicinity, *in* Guidebook to the geology of the Carrizo Plains and San Andreas Fault: San Joaquin Geol. Soc. and Pacific Sect., Amer. Assoc. of Petroleum Geologists and Soc. Exploration Paleontologists and Mineralogists (AAPG-SEPM), p. 5-12

Diller, Joseph S., 1895, Description of the Lassen Peak sheet: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 15

—— 1902, Topographic development of the Klamath Mountains: U.S. Geol. Surv. Bull. 196, 69 p.

—— 1906, Description of the Redding quadrangle, California: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 138, 14 p.

Drewes, Harald, 1963, Geology of the Funeral Peak quadrangle, California, on the east flank of Death Valley: U.S. Geol. Surv. Prof. Pap. 413, 78 p.

Driver, Herschel L., 1943, Inglewood oil field, *in* Jenkins, 1943, p. 306-309

Durham, D. L., and Yerkes, R. F., 1964, Geology and oil resources of the eastern Puente Hills area, southern California: U.S. Geol. Surv. Prof. Pap. 420-B, 62 p.

Durham, J. Wyatt, 1954, The marine Cenozoic of southern California: *in* Jahns, 1954, Ch. 3, p. 23-31

Durham, J. Wyatt, Jahns, Richard H., and Savage, Donald E., 1954, Marine-nonmarine relationships in the Cenozoic section of California: *in* Jahns, 1954, Ch. 3, p. 59-71

Dutcher, L. C., and Garrett, A. A., 1963, Geologic and hydrologic features of the San Bernardino area, California, with special reference to underflow across the San Jacinto Fault: U.S. Geol. Surv. Water-Supply Pap. 1419, 114 p.

Eaton, J. E., 1928, Divisions and duration of the Pleistocene in southern California: Amer. Assoc. Petroleum Geologists Bull., v. 12, p. 111-141

Ellis, Arthur J., and Lee, Charles H., 1919, Geology and ground-waters of the western part of San Diego County, California: U.S. Geol. Surv. Water-Supply Pap. 446, 320 p.

Emery, K. O., 1960, The sea off southern California—a modern habitat of petroleum: New York, John Wiley and Sons, 366 p.

Emiliani, C., and Epstein, S., 1953, Temperature variations in the lower Pleistocene of southern California: J. Geol., v. 61, p. 171-181

Evenson, R. E., 1959, Geology and ground-water features of the Eureka area, Humboldt County, California: U.S. Geol. Surv. Water-Supply Pap. 1470, 80 p.

Evernden, J. F., and Curtis, G. H., in press, The potassium-argon dating of late Cenozoic rocks in East Africa and Italy: Curr. Anthrop.

Evernden, J. F., and James, G. T., 1964, Potassium-argon dates and the Tertiary floras of North America: Amer. J. Sci., v. 262, p. 945-974

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Amer. J. Sci., v. 262, p. 145-198

Fairbanks, H. W., 1898, Geology of a portion of the southern Coast Ranges: J. Geol., v. 6, p. 565-566

—— 1904, Description of the San Luis quadrangle: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 101

Fenneman, N. M., 1931, Physiography of the western United States: New York, McGraw-Hill Book Co., 534 p.

Flint, R. F., 1957, Glacial and Pleistocene geology: New York, John Wiley and Sons, 553 p.

Frink, John W., and Kues, Harry A., 1954, Corcoran clay—a Pleistocene lacustrine deposit in San Joaquin Valley, California: Amer. Assoc. Petroleum Geologists Bull., v. 38, p. 2357-2371

Gardner, Robert A., and Bradshaw, Kenneth E., 1954, Characteristics and vegetation relationships of some Podzolic soils near the coast of northern California: Soil Sci. Soc. Amer. Proc., v. 18, p. 320-325

Garrison, Lowell E., 1962, The Marysville (Sutter) Buttes, Sutter County, California: California Div. Mines Geol. Bull. 181, p. 69-72

Gealey, William Kelso, 1951, Geology of the Healdsburg quadrangle, California: California Div. Mines Bull. 161, p. 1-50

Gilbert, Charles M., 1938, Welded tuff in eastern California: Geol. Soc. Amer. Bull., v. 49, p. 1829-1862

—— 1941, Late Tertiary geology southeast of Mono Lake, California: Geol. Soc. Amer. Bull., v. 52, p. 781-816

Gilbert, Grove Karl, 1914, The transportation of debris by running water: U.S. Geol. Surv. Prof. Pap. 86, 263 p.

—— 1917, Hydraulic-mining debris in the Sierra Nevada: U.S. Geol. Surv. Prof. Pap. 105, 154 p.

Glen, William, 1959, Pliocene and lower Pleistocene of the western part of the San Francisco Peninsula: Univ. California Publ. Geol. Sci., v. 36, No. 2, p. 147-198

Grant, U. S., IV, and Gale, Hoyt Rodney, 1931, Catalogue of the marine Pliocene and Pleistocene mollusca of California and adjacent regions: San Diego Nat. Hist. Soc. Mem., v. 1, 1036 p.

Grinsfelder, S., 1943, Dominguez oil field, *in* Jenkins, 1943, p. 318-319

Hall, Clarence A., Jr., 1958, Geology and paleontology of the Pleasanton area, Alameda and Contra Costa Counties, California: Univ. California Publ. Geol. Sci., v. 34, p. 1-90

Hershey, Oscar H., 1900, Ancient alpine glaciers of the Sierra Costa Mountains in California: J. Geol., v. 8, p. 42-56

—— 1903a, Some evidence of two glacial stages in the Klamath Mountains in California: Amer. Geologist, v. 31, p. 139-156

—— 1903b, The relation between certain river terraces and the glacial series in northwestern California: J. Geol., v. 11, p. 431-458

—— 1903c, Certain river terraces of the Klamath region, California: Amer. J. Sci., 4th ser., v. 16, p. 240-250

—— 1904, The river terraces of the Orleans Basin, California: Univ. California Publ. Dept. Geol. Bull., v. 3, p. 423-475

Hibbard, C. W., Ray, D. E., Savage, D. E., Taylor, D. W., and Guilday, J. E., this volume, Quaternary mammals of North America

Higgins, Charles G., 1952, Lower course of the Russian River, California: Univ. Cailfornia Publ. Geol Sci., v. 29, No. 5, p. 181-264

—— 1960, Ohlson Ranch Formation, Pliocene, northwestern Sonoma County, California: Univ. California Publ. Geol. Sci., v. 36, p. 199-232

—— 1961, San Andreas Fault north of San Francisco, California: Geol. Soc. Amer. Bull., v. 72, p. 51-68

Hill, Mason L., and Dibblee, T. W., Jr., 1953, San Andreas, Garlock, and Big Pine Faults, California, a study of the character, history, and tectonic significance of their displacements: Geol. Soc. Amer. Bull., v. 64, p. 443-458

Hinds, Norman E. A., 1933, Geologic formations of the Redding-Weaverville districts, northern California: California J. Mines Geol. (State Mineralogist's Rep.), v. 29, p. 77-122

—— 1952, Evolution of the California landscape: California Div. Mines Bull. 158, 240 p.

Holmes, L. C., Nelson, J. W., *et al.*, 1915, Reconnaissance soil survey of the Sacramento Valley, California: U.S. Dept. Agric., Bur. Soils, Advance Sheets, Field Operations, 1915, 148 p.

Holway, R. S., 1911, An extension of the known area of Pleistocene glaciation to the Coast Ranges of California: Amer. Geogr. Soc. Bull., v. 43, p. 161-170 (from Davis, S. N., 1958).

Hoots, H. W., 1930, Geology and oil resources along the southern border of San Joaquin Valley, California: U.S. Geol. Surv. Bull. 812, p. 243-332

Hoots, Harold W., Bear, Ted L., and Kleinpell, William D., 1954, Geological summary of the San Joaquin Valley, California: *in* Jahns, 1954, Ch. 2, p. 113-129

Howard, Arthur, 1951, Development of the landscape of the San Francisco Bay Counties: California Div. Mines Bull. 154, p. 95-106

Hudson, F. S., 1955, Measurement of the deformation of the Sierra Nevada, California, since middle Eocene: Geol. Soc. Amer. Bull., v. 66, p. 835-870

—— 1960, Post-Pliocene uplift of the Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 71, p. 1547-1574

Huey, Arthur S., 1948, Geology of the Tesla quadrangle, California: California Div. Mines Bull. 140, 75 p.

Irwin, William P., 1960, Geologic reconnaissance of the northern Coast Ranges and Klamath Mountains, California, with a summary of the mineral resources: California Div. Mines Bull. 179, 80 p.

Jahns, Richard H. (ed.), 1954, Geology of southern California: California Div. Mines Bull. 170, 10 chapters, separately paged

Jenkins, Olaf P., *et al.*, 1943, Geologic formations and economic development of the oil and gas fields of California: California Div. Mines Bull. 118, 773 p.

Jennings, Charles W., 1958, San Luis Obispo sheet, geologic map of California (1:250,000), Olaf P. Jenkins edition: California Div. Mines Geol.

—— 1959, Santa Maria sheet, geologic map of California (1:250,000), Olaf P. Jenkins edition: California Div. Mines Geol.

Jennings, Charles W., and Burnett, John L., 1961, San Francisco sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

Jennings, Charles W., and Strand, Rudolph G., 1958, Santa Cruz sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

—— 1960, Ukiah sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

Johnson, F. A., 1943, Petaluma region: *in* Jenkins, 1943, p. 622-627

Johnson, Harry R., 1943, Marysville Buttes (Sutter Buttes) gas field: *in* Jenkins, 1943, p. 610-615

Kew, William S. W., 1924, Geology and oil resources of a part of Los Angeles and Ventura Counties, California: U.S. Geol. Surv. Bull. 753, 202 p.

King, Philip B., 1958, Evolution of modern surface features of western North America: *in* Hubbs, C. L. (ed.), Zoogeography: Amer. Assoc. Adv. Sci. Publ. 51, p. 3-60

—— 1959, The Evolution of North America: Princeton, N.J., Princeton Univ. Press, 190 p.

—— this volume, Tectonics of Quaternary time in middle North America

Knopf, Adolph, 1918, A geologic reconnaissance of the Inyo Range and the eastern slope of the Sierra Nevada, California, with a section on the stratigraphy of the Inyo Range by Edwin Kirk: U.S. Geol. Surv. Prof. Pap. 110, 130 p.

Koenig, James B., 1963, Santa Rosa sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

Kundert, Charles J., 1955, Bakersfield sheet, geologic map of California (1:250,000), prelim. uncolored ed.: California Div. Mines

Kunkel, Fred, and Upson. J. E., 1960, Geology and ground-water in Napa and Sonoma Valleys, Napa and Sonoma Counties, California: U.S. Geol. Surv. Water-Supply Pap. 1495, 252 p.

Lachenbruch, M. C., 1962, Geology of the west side of the Sacramento Valley, California: *in* Bowen, 1962, p. 53-66

Lawson, Andrew C., 1893, The post-Pliocene diastrophism of the coast of southern California: Univ. California, Dept. Geol. Bull., v. 1, p. 115-160

—— 1894, The geomorphogeny of the coast of northern California: Univ. California Dept. Geol. Bull., v. 1, p. 241-272

—— 1904, The geomorphogeny of the upper Kern Basin: Univ. California Dept. Geol. Sci. Bull., v. 3, p. 291-376

—— 1914, Description of the San Francisco District: U.S. Geol. Surv., Geol. Atlas of the United States, Folio 193 (Field edition, 1915, 180 p.)

Le Conte, Joseph, 1873, On some of the ancient glaciers of the Sierra: Amer. J. Sci., 3rd ser., v. 5, p. 325-339

Lindgren, Waldemar, 1894, Description of the Sacramento sheet: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 5, p. 2-3

—— 1896, Description of the Pyramid Peak quadrangle: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 31, p. 1-6

—— 1897, Description of the Truckee quadrangle: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 37, p. 2-8

—— 1900, Description of the Colfax quadrangle: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 66, 10 p.

—— 1911, The Tertiary gravels of the Sierra Nevada of California: U.S. Geol. Surv. Prof. Pap. 73, 226 p.

Lindgren, Waldemar, and Turner, H. W., 1895, Description of the Marysville sheet: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 17, 2 p.

Long, Joseph S., Jr., and Carpenter, David W., 1963, Geology of the Mile 18 Pumping Plant area: Geol. Soc. Sacramento, Richter, Raymond C. (ed.), Guidebook to the annual field trip for 1963, central portion of the Great Valley of California, p. 53-56

Louderback, George D., 1951, Geologic history of San Francisco Bay: California Div. Mines Bull. 154, p. 75-94

MacDonald, Gordon A., 1963, Geology of the Manzanita Lake quadrangle, California (1:62,500): U.S. Geol. Surv. Geol. Quadrangle Map GQ 248

MacGinitie, H. D., 1937, The flora of the Weaverville beds of Trinity County, California, *in* Eocene flora of western America: Carnegie Instn. Contr. Paleont., Publ. 465, p. 84-151

—— 1943, Central and southern Humboldt County: *in* Jenkins, 1943, p. 633-635

Manning, John C., 1963, Resume of ground-water hydrology in Salinas Valley, California: Amer. Assoc. Petroleum Geologists, Soc. Exploration Mineralogists and Paleontologists, Pacific Sect. *in* Payne, Max B. (ed.), Guidebook to the geology of the Salinas Valley and the San Andreas Fault, annual spring field trip, May 24-25, 1963, p. 106-109

Martin, Bruce, 1916, The Pliocene of middle and northern California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 9, p. 215-259

Matthes, Francois E., 1930, Geologic history of the Yosemite Valley: U.S. Geol. Surv. Prof. Pap. 160, 137 p.

—— 1938, The geologic history of Mt. Whitney: Sierra Club Bull., v. 22, p. 1-18

—— 1939, Report of the Committee on Glaciers: Amer. Geophys. Union, Trans. for 1939, pt. III, p. 518-523

—— 1942, Glaciers, *in* Meinzer, O. E. (ed.), Physics of the earth—hydrology: New York, McGraw-Hill Book Co., p. 149-219 (Reprinted 1949 by Dover Publications, Inc., New York)

—— 1950, The incomparable valley, a geologic interpretation of the Yosemite, edited by Fritiof Fryxell, including 24 photographs by Ansel Adams: Berkeley, Univ. California Press, 160 p.

—— 1960, Reconnaissance of the geomorphology and glacial geology of the San Joaquin Basin, Sierra Nevada, California: U.S. Geol. Surv. Prof. Pap. 329, 62 p.

Maxson, John H., 1933, Economic geology of portions of Del Norte and Siskiyou Counties, northwesternmost California: California J. Mines Geol. (State Mineralogist's Rep.), v. 29, p. 123-160

McAllister, J. F., 1936, Glacial history of an area near Lake Tahoe: Stanford University M.A. thesis

McVath, V. E., 1959-1960, Reconnaissance geology of parts of Almanor, Greenville, Kettle Rock, Chester, and Westwood quadrangles: California Division of Mines, unpublished report

Mendenhall, W. C., Dole, R. B., and Stabler, Herman, 1916, Ground water in the San Joaquin Valley, California: U.S. Geol. Surv. Water-Supply Pap. 398, 310 p.

Miller, D. H., 1955, Snow cover and climate in the Sierra Nevada, California: Univ. California Publ. Geogr., v. 11, p. 1-218

Minard, Claude R., Jr., 1964, The erosional and depositional history of the coast of northern California: Univ. California Hydraulic Engineering Lab. Tech. Rep. HEL—2-10, 63 p.

Moore, James G., 1963, Geology of the Mount Pinchot quadrangle, southern Sierra Nevada, California: U.S. Geol. Surv. Bull. 1130, 152 p.

Morrison, Roger B., this volume, Quaternary geology of the Great Basin

Muir, John, 1872, Living glaciers of California, Overland, v. 9, p. 547-549

—— 1874, Studies in the Sierra: Overland, v. 12, p. 393-403, 489-500; v. 13, p. 67-79, 174-184, 393-401, 530-540; v. 14, p. 64-73

—— 1880, Ancient glaciers of the Sierra: Californian, v. 2, p. 550-557

Nelson, J. W., Dean, Walter C., and Eckmann, E. C., 1921, Reconnaissance soil survey of the upper San Joaquin Valley, California: U.S. Dept. Agric., Bur. Soils (Advance Sheets—Field Operations) 1917

Nelson, Richard N., 1925, Geology of the hydrographic basin of the upper Santa Ynez River, California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 15, p. 327-396

Oakeshott, Gordon B., 1958, Geology and mineral deposits of San Fernando quadrangle, Los Angeles County, California: California Div. Mines Bull. 172, 147 p.

Ogle, Burdette A., 1953, Geology of Eel River area, Humboldt County, California: California Div. Mines Bull. 164, 128 p.

Olmsted, F. H., 1958, Geologic reconnaissance of San Clemente Island, California: U.S. Geol. Surv. Bull. 1071-B, p. 55-68

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U.S. Geol. Surv. Water-Supply Pap. 1497, 241 p.

Orr, Phil C., 1960, Late Pleistocene marine terraces on Santa Rosa Island, California: Geol. Soc. Amer. Bull., v. 71, p. 1113-1120

Ortalda, Robert A., 1949, Geology of the northern part of the Morgan Hill quadrangle, California: Berkeley, Univ. California M.A. thesis, 55 p.

Page, R. W., 1963, Geology and ground-water appraisal of the Naval Air Missile Test Center Area, Point Mugu, California: U.S. Geol. Surv. Water-Supply Pap. 1619-S, 40 p.

Peck, Joseph H., Jr., 1960, Paleontology and correlation of the Ohlson Ranch Formation: Univ. California Publ. Geol. Sci., v. 36, p. 233-242

Piper, A. M., Gale, H. S., Thomas, H. E., and Robinson, T. W., 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geological Surv. Water-Supply Pap. 780, 230 p.

Poland, J. F., Garrett, A. A., and Sinnott, Allen, 1959, Geology, hydrology, and chemical character of ground-waters in the Torrance–Santa Monica area, California: U.S. Geol. Surv. Water-Supply Pap. 1461, 425 p.

Poland, J. F., and Green, J. H., 1962, Subsidence in the Santa Clara Valley, California, a progress report: U.S. Geol. Surv. Water-Supply Pap. 1619-C, 16 p.

Poland, J. F., Piper, A. M., *et al.*, 1956, Ground-water geology of the Coastal Zone, Long Beach–Santa Ana area, California: U.S. Geol. Surv. Water-Supply Pap. 1109, 162 p.

Putnam, William C., 1942, Geomorphology of the Ventura region, California: Geol. Soc. Amer. Bull., v. 53, p. 691-754

—— 1949, Quaternary geology of the June Lake District, California: Geol. Soc. Amer. Bull., v. 60, p. 1281-1302

—— 1950, Moraine and shoreline relationships at Mono Lake, California: Geol. Soc. Amer. Bull., v. 61, p. 115-122

—— 1960a, Origin of Rock Creek and Owens River Gorges, Mono County, California: Univ. California Publ. Geol. Sci., v. 34, p. 221-280

—— 1960b, Faulting and Pleistocene glaciation in the east-central Sierra Nevada of California, U.S.A.: 21st Intern. Geol. Congr. Copenhagen, Rep., pt. 21, p. 270-274

—— 1962, Late Cenozoic geology of McGee Mountain, Mono County, California: Univ. California Publ. Geol. Sci., v. 40, p. 181-218

Radbruch, Dorothy H., 1957, Areal and engineering geology of the Oakland West quadrangle, California (1:24,000): U.S. Geol. Surv. Misc. Geol. Inv. Map I-239

Reed, Ralph D., 1933, Geology of California: Tulsa, Oklahoma, Amer. Assoc. Petroleum Geologists, 355 p.

Reed, Ralph D., and Hollister, J. S., 1936, Structural evolution of southern California: Tulsa, Oklahoma, Amer. Assoc. Petroleum Geologists, 157 p.

Reiche, Parry, 1950, Geology of part of the Delta-Mendota Canal, near Tracy, California: California Div. Mines Spec. Rep. No. 2, 12 p.

Rinehart, C. Dean, and Ross, Donald C., 1957, Geology of the Casa Diablo Mountain quadrangle, California (1:62,500): U.S. Geol. Surv. Geol. Quadrangle Map, No. GQ 99

—— 1964, Geology and mineral deposits of the Mount Morrison quadrangle, Sierra Nevada, California; with a section on a gravity study of Long Valley, by L. C. Pakiser: U.S. Geol. Surv. Prof. Pap. 385, 106 p.

Rubin, Meyer, and Alexander, Corrinne, 1960, U.S. Geological Survey radiocarbon dates v: Amer. J. Sci., Radiocarbon Suppl., v. 2, p. 129-185

Russell, Israel C., 1885a, Existing glaciers of the United States: U.S. Geol. Surv. 5th Ann. Rep., p. 303-355

—— 1885b, Geologic history of Lake Lahontan, a Quaternary lake of northwestern Nevada: U.S. Geol. Surv. Monogr. 11, 288 p.

—— 1889, Quaternary history of Mono Valley, California: U.S. Geol. Surv. 8th Ann. Rep., p. 251-394

Russell, R. D., and VanderHoof, V. L., 1931, A vertebrate fauna from a new Pliocene formation in northern California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 20, p. 11-21

Safonov, Anatole, 1962, The challenge of the Sacramento Valley, California: *in* Bowen, 1962, p. 77-97

Savage, Donald E., 1951, Late Cenozoic vertebrates of the San Francisco Bay region: Univ. California Publ., Dept. Geol. Sci. Bull., v. 28, p. 215-314

Schlocker, J., Bonilla, M. G., and Radbruch, D. H., 1958, Geology of the San Francisco North quadrangle, California (1:24,000): U.S. Geol. Surv. Misc. Geol. Inv. Map I-272

Sharp, Robert P., 1960, Pleistocene glaciation in the Trinity Alps of northern California: Amer. J. Sci., v. 258, p. 305-340

Sharp, Robert P., Allen, Clarence R., and Meier, Mark F., 1959, Pleistocene glaciers on southern California mountains: Amer. J. Sci., v. 257, p. 81-94

Sharp, Robert P., and Birman, J. H., 1963, Addition to the classical sequence of Pleistocene glaciations, Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 74, p. 1079-1086

Smith, David D., 1960, The geomorphology of part of the San Francisco Peninsula, California: Stanford University Ph.D. thesis

Stirton, R. A., 1936, Succession of North American continental Pliocene mammalian faunas: Amer. J. Sci., 5th ser. v. 32, p. 161-206

—— 1939, Cenozoic mammal remains from the San Francisco Bay region: Univ. California Publ., Dept. Geol. Sci. Bull., v. 24, p. 339-410

—— 1952, Are Petaluma horse teeth reliable in correlation?: Amer. Assoc. Petroleum Geologists Bull., v. 36, p. 2011-2025

Stock, Chester, 1930, Rancho La Brea, a record of Pleistocene life in California: Los Angeles Mus. Publ. 1, 82 p.

Stolz, Harry P., 1943, Long Beach oil field: *in* Jenkins, 1943, p. 320-324

Strand, Rudolph G., 1962, Redding sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

—— 1963, Weed sheet (1:250,000), geologic map of California, Olaf P. Jenkins edition: California Div. Mines Geol.

Taliaferro, N. L., 1941, Geologic history and structure of the central Coast Ranges of California: *in* Jenkins, 1943, p. 119-162

—— 1943, Bradley-San Miguel District: *in* Jenkins, 1943, p. 456-462

Thomas, R. G., Marliave, E. C., James, L. B., and Bean, R. T., 1954, Geology and hydrology of Ventura County: *in* Jahns, 1954, Ch. 6, p. 19-28

Thompson, George A., and Talwani, Manik, 1964, Geology of the crust and mantle, western United States: Science, v. 146, p. 1539-1549

Thompson, George A., and White, D. E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U.S. Geol. Surv. Prof. Pap. 458-A, 52 p.

Tocher, Don, 1959, Seismic history of the San Francisco region: California Div. Mines Spec. Rep. 57, p. 41-48

Trask, Parker D., 1926, Geology of Point Sur quadrangle, California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 16, p. 119-186

Trask, Parker D., and Rolston, Jack W., 1951, Engineering geology of San Francisco Bay, California: Geol. Soc. Amer. Bull., v. 62, p. 1079-1110

Travis, Russell B., 1952, Geology of the Sebastopol quadrangle, California: California Div. Mines Bull. 162, 33 p.

Turner, H. W., 1897, Description of the Downieville quadrangle: U.S. Geol. Surv. Geol. Atlas of the United States, Folio No. 37, p. 3-8

—— 1898, Description of the Bidwell Bar quadrangle: U.S. Geol. Surv., Geol. Atlas of the United States, Folio No. 43, p. 3-6

—— 1900, The Pleistocene geology of the south central Sierra Nevada with especial reference to the origin of Yosemite Valley: California Acad. Sci. Proc., Ser. 3, Geol., v. 1, p. 261-321

Turner, H. W., and Ransome, F. L., 1898, Description of the Big Trees quadrangle: U.S. Geol. Surv. Geol. Atlas of the United States, Folio No. 51, p. 3-8

Upson, J. E., 1949, Late Pleistocene and Recent changes of sea level along the coast of Santa Barbara County, California: Amer. J. Sci., v. 247, p. 94-115

—— 1951a, Geology and ground-water resources of the south-coast basins of Santa Barbara County, California; with a section on surface-water resources by H. G. Thomasson, Jr.: U.S. Geol. Surv. Water-Supply Pap. 1108, 144 p.

—— 1951b, Former marine shore lines of the Gaviota quadrangle, Santa Barbara County, California: J. Geol., v. 59, p. 415-446

Upson, J. E., and Kunkel, Fred, 1955, Ground water of the Lower Lake–Middletown area, Lake County, California: U.S. Geol. Surv. Water-Supply Pap. 1297, 81 p.

Upson, J. E., and Thomasson, H. G., Jr., 1951, Geology and water resources of the Santa Ynez River Basin, Santa Barbara County, California: U.S. Geol. Surv. Water-Supply Pap. 1107, 194 p.

Valentine, James W., 1961, Paleoecologic molluscan geography of the California Pleistocene: Univ. California Publ. Geol. Sci., v. 34, p. 309-442

Valentine, James W., and Meade, Robert F., 1961, California Pleistocene paleotemperatures: Univ. California Publ. Geol. Sci., v. 40, p. 1-46

VanderHoof, V. L., 1933a, Additions to the fauna of the Tehama upper Pliocene of northern California: Amer. J. Sci., 5th ser., v. 25, p. 382-384

—— 1933b, A skull of *Pliohippus tantalus* from the later Tertiary of the Sierran foothills of California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 23, p. 183-193

—— 1955, The major earthquakes of California; a historical summary: California Div. Mines Bull. 171, p. 137-141

Wahrhaftig, Clyde, 1963, Origin of stepped topography of the west-central Sierra Nevada, California (abst.): Geol. Soc. Amer. Spec. Pap. 73, p. 71

—— in press, The stepped topography of the southern Sierra Nevada, California, and its origin: Geol. Soc. Amer. Bull.

Weaver, Charles E., 1949, Geology of the north Coast Ranges immediately north of the San Francisco Bay region, California: Geol. Soc. Amer. Mem. 35, 242 p.

Weaver, D. K., and Wilhelm, V. H., 1943, Huntington Beach oil field: *in* Jenkins, 1943, p. 329-331

Webb, Robert W., 1950, Volcanic geology of Toowa Valley, southern Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 61, p. 349-357

Wells, Francis G., Hotz, Preston E., and Cater, Fred W., Jr., 1949, Preliminary description of the geology of the Kerby quadrangle, Oregon: Oregon (State) Dept. Geol. Min. Ind., Bull. 40, 23 p.

Whitten, C. A., 1949, Horizontal earth movement in California: Coast and Geodetic Surv. J., April 1949, No. 2, p. 84-88

Williams, Howel, 1929, Geology of the Marysville Buttes, California: Univ. California Publ., Dept. Geol. Sci. Bull., v. 18, No. 5, p. 103-220

—— 1949, Geology of MacDoel quadrangle, California: California Div. Mines Bull. 151, p. 7-60

Wilson, Ivan F., 1943, Geology of the San Benito quadrangle, California: California J. Mines Geol. (State Mineralogist's Rep.) v. 39, No. 2, p. 183-270

Winterer, E. L., and Durham, D. L., 1962, Geology of southeastern Ventura Basin, Los Angeles County, California: U.S. Geol. Surv. Prof. Pap. 334-H, p. 275-336

Woodford, A. O., Schoellhamer, J. E., Vedder, J. G., and Yerkes, R. F., 1954, Geology of the Los Angeles Basin: *in* Jahns, 1954, Ch. 2, p. 65-81

Woodring, W. P., 1952, Plio-Pleistocene boundary in California Coast Ranges: Amer. J. Sci., v. 250, p. 401-410

Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., 1946, Geology and paleontology of Palos Verdes Hills, California: U.S. Geol. Surv. Prof. Pap. 207, 145 p.

Woodring, W. P., and Bramlette, M. N., 1950, Geology and paleontology of the Santa Maria District, California: U.S. Geol. Surv. Prof. Pap. 222, 185 p.

Woodring, W. P., Roundy, P. V., and Farnsworth, H. R., 1932, Geology and oil resources of the Elk Hills, California, including Naval Petroleum Reserve No. 1: U.S. Geol. Surv. Bull. 835, 82 p.

Woodring, W. P., Stewart, Ralph, and Richards, R. W., 1940, Geology of the Kettleman Hills oil field, California: U.S. Geol. Surv. Prof. Pap. 195, 170 p.

SUMMARY

California is in the eugeosynclinal part of the Cordilleran mobile belt and has undergone orogenic activity periodically from Jurassic time; the latest major orogeny extended from mid-Tertiary to the present. Physiographic provinces include: the Sierra Nevada, a tilted fault block underlain by granitic and metamorphic rocks; the Great Valley, a sedimentary basin with thick Quaternary alluvium; the Klamath Mountains; the Coast Ranges, northwest-trending mountains of Mesozoic and Cenozoic rocks separated by structural valleys; the Transverse Ranges, an east-trending belt of mountains and structural valleys; the Peninsular Range, a tilted fault block similar to the Sierra Nevada; and the Province of Southern California, a largely submerged area of basin-and-range topography that includes several islands, the continental shelf, and a triangular lowland on the mainland. Active transcurrent faults, most important of which is the San Andreas Fault, influence the geology and topography of coastal California.

Quaternary volcanic rocks on the east side of the Sierra Nevada include basaltic flows 1.2 to 2.3 million years old north of Lake Tahoe (the Lousetown Formation); deformed basalt flows 2.6-3.2 million years old overlain unconformably by tilted and faulted ignimbrite (the Bishop Tuff) 700,000 years old, which is overlain in turn by tuff rings, obsidian domes, and a dacite volcano (the Mono Craters and Mammoth Mountains) 5,000-370,000 years old, all between Mono Lake and Bishop; and basaltic flows and cinder cones in Owens Valley. Quaternary volcanic rocks on the western slope of the Sierra Nevada include basaltic flows 2.9 to 3.8 million years old in the basins of the San Joaquin and Kern Rivers. The dated volcanic rocks established that the canyon-cutting stage on the west side of the Sierra Nevada was well advanced 3.5 million years ago and that much of the faulting on the east side took place in the last 2.6 million years.

Six glaciations have been recognized in the Sierra Nevada, not counting post-Altithermal advances. These are: the McGee, represented by ancient till on high ridge-tops resting on basalt 2.5 million years old; the Sherwin, at lesser altitudes above valley bottoms and without preserved morainal topography, overlain by the Bishop Tuff (700,000 years old) at its type locality; the Mono Basin, with well-preserved but subdued morainal topography; the Tahoe, with well-preserved morainal topography and abundant weathered granodiorite boulders; the Tenaya; and the Tioga, with fresh boulders and nearly unmodified landforms. The last three glaciations are correlated with the Wisconsin; the Tahoe rests on basalt 60,000 or 90,000 years old; the Tenaya is intermediate in post-depositional weathering between the Tahoe and the Tenaya. Three small advances subsequent to the altithermal have been recognized.

The Quaternary alluvium in the Great Valley ranges up to 1,500 m or more in thickness and is the top of a generally parallel succession of Cretaceous and Cenozoic rocks many thousands of meters thick. Alluvium on the east side of the valley is the finest component of glacial outwash from the Sierra Nevada and is separated by erosional unconformities (with soils of different degrees of development) into the Turlock Lake, Riverbank, and Modesto Formations and Recent alluvium. Alluvium on the west side of the valley was deposited by mudflows and ephemeral streams and represents an apparently continuous succession broken only by angular unconformities along the margin of the Coast Ranges. The folded and locally overturned Quaternary along the southwest margin of the valley is named the Tulare Formation. Within the Tulare and also within the Turlock Lake Formation is a diatomaceous clay, the Corcoran Clay, which underlies much of the southern half of the valley at 60-270 m below the surface; it is about 600,000 years old and contains an Irvingtonian or Rancholabrean fauna.

The structural valleys of the southern Coast Ranges are bordered in part by moderately deformed Plio-Pleistocene sediments, 300 m or more thick, derived from nearby mountains. Over much of the Coast Ranges these rest unconformably on tightly folded upper Pliocene and older rocks, indicating that the orogeny that preceded their deposition was greater than that which followed. In the southeastern Coast Ranges the Plio-Pleistocene rocks are conformable on underlying marine Pliocene and Miocene rocks and are folded with them.

Younger undeformed alluvium several hundred meters thick underlies the centers of the valleys. Marine terraces along the coast have altitudes up to 300 m and are slightly deformed. As many as five or six terraces are present locally. No sign of marine inundation inland is found to correspond with these terraces. Postglacial eustatic sea-level rise is indicated by drowned valleys and alluvium-filled gorges descending to nearly 100 m below sea level.

The northern Coast Ranges and Klamath Mountains were above sea level during most of the upper Cenozoic, and their history is largely one of erosion, uplifting and warping, and volcanism. Deformed early-Quaternary formations, in part marine, are found in a few coastal basins. Marine terraces are common along the coast, up to 300 m in altitude, and are only locally deformed. A broad continental shelf indicates that the coastline was eroded back to about its present position after each uplift.

Late-Pliocene and Quaternary volcanic fields in the southern part of the northern Coast Ranges (Sonoma Volcanics and Clear Lake Volcanic Field) are associated with continental sedimentation in local basins; they include as their youngest members well-preserved dacitic strato-volcanoes and endogenous domes and rhyolitic and basaltic flows and cinder cones. Earlier flows and sediments are considerably deformed. Small structural valleys entirely enclosed by mountains are bordered by deformed continental Plio-Pleistocene(?) deposits and are underlain by several tens to a few hundred meters of alluvium. Several streams are antecedent to Quaternary upwarps.

The Klamath Mountains had numerous valley glaciers, and a few peaks in the northern Coast Ranges were glaciated. Wisconsin firn limit ranged from 1,600 to 2,000 m.

In Southern California the marine lower Pleistocene is as much as 1,500-1,850 m thick in the Ventura Basin and as much as 900 m thick beneath the Los Angeles Basin. Included in it are the Santa Barbara Formation, the San Pedro Sand, Timms Point Silt, and Lomita Marl. It is the top of an enormously thick sedimentary succession that was continuous from the Miocene and has been folded, locally overturned, and faulted. It interfingers to the north and east with continental gravels as much as 2,000 m thick.

As many as 13 and 20 marine terraces have been recognized on some parts of the Southern California coast, ranging in altitude up to 450 m. The lowest main terrace, overlain by the Palos Verdes Sand (Upper San Pedro) is about 30 m high and corresponds to the Sangamon Interglacial. It has been locally deformed into anticlines and monoclines. The fossiliferous asphalt of Rancho La Brea, in the northern part of the Los Angeles Basin, is contemporaneous with or slightly younger than the Palos Verdes Sand. Subsequent to withdrawal of the sea from the lowest terrace, rivers in the Los Angeles Basin cut trenches through the terrace at least 55 m deep. These have subsequently been filled.