1. INVESTIGATIONS AND PROBLEMS OF SOUTHERN CALIFORNIA GEOLOGY *

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HISTORICAL SKETCH

Period of Early Settlement. Recognition of geologic features and processes by the peoples of southern California dates back at least several thousand years, when Indian tribes lived in some of the coastal areas and on the shores of now-extinct lakes farther inland. These early inhabitants were well aware of earthquakes, floods, landslides, and other natural phenomena, as well as unusual elements of the terrain, and they attempted to explain these things by means of various myths, many of which appear to have been founded upon more careful observations than do some of the scientific explanations of much more recent times!

Later tribes became increasingly aware of rock and mineral materials, and showed considerable skill in correlating their physical properties with specific uses. Thus granite and steatite were converted into utensils, slate and schist into quarrying tools, and obsidian and silica minerals into weapons. Clay was used for making ceramic ware, and asphaltum from numerous seeps was used for waterproofing and as an adhesive. Natural pigments, salt, and gem materials also were in demand. The techniques of search for better materials, and of mining and preparing these materials, were gradually improved, and ultimately at least 131 mine or quarry localities were known to the California Indians (Heizer and Treganza, 1944, pp. 298, 303-340).

Spanish settlement of the region began with the Portolá expedition in 1769, long after the explorations of coastal areas by Cabrillo (1542), Viscaíno (1602), and others. From this time until shortly after the end of Spanish rule in 1847, southern California was a slowly developing agricultural province characterized by large ranchos. The newcomers commonly followed the example of the Indians in selecting areas for settlement, and they used much the same sources of water, bathed in the same hot springs, and worked some of the same mineral deposits that had been known to the Indians. A few of them also indulged in a little mining for placer gold in Imperial County as early as 1775, and later on some mining was done in Recent stream gravels north of Los Angeles and in conglomerates of early Tertiary age in San Diego County.

Period of Geologic Exploration and Early Description. The discovery of gold in the Sierra Nevada in 1848 initiated a period of profound changes in southern California life. The Americans who had come to the coastal areas during earlier years were joined by thousands upon thousands of others, Los Angeles and other towns became important trading centers, and new settlements were founded as most of the large ranchos were divided into numerous smaller holdings. Prospecting and mining flourished in many parts of the region, and new mining camps appeared in the country east and southeast of the Sierra Nevada, as well as in the Coast Ranges to the west. Metal mining was dominant, but important discoveries of petroleum, salines, and other nonmetallic substances also were made.

The earliest systematic work on southern California geology was done in connection with several surveys of mineralized areas and routes of transportation. The expeditions in 1853 and 1854 for railroad routes to the Pacific Ocean yielded descriptions of rocks, fossils, and mineral deposits, and marked the real beginning of integrated observations on the geologic history of the region. From these surveys also came the first reasonably accurate geologic maps of southern California areas (Blake, 1856; Antisell, 1857), and it is interesting to compare them with the much more detailed map data presented years later by Darton (1916, 1933) for the country along some of the same routes. Additional systematic investigations were made in the fifties by the first State Geological Survey, under the direction of J. B. Trask, and in the sixties by State Geologist J. D. Whitney and his staff.

Southern California was linked by rail to San Francisco in 1876 and directly to the east in 1881, and soon afterward tremendous increases in population stimulated geological investigations on many fronts. The U. S. Geological Survey, which had been organized in 1879, sent numerous workers into the region, and by the turn of the century important contributions had been made by Waldemar Lindgren and H. W. Turner in the Sierra Nevada and areas to the east and southeast, G. F. Becker in the Sierra Nevada and the Coast Ranges, and G. K. Gilbert and I. C. Russell in parts of the Basin-Range country. Paleontologic studies had been made by T. A. Conrad, C. D. Walcott, C. A. White, W. H. Dall, T. W. Stanton, and others.

The State Mining Bureau, organized in 1880, was responsible for widespread investigations by H. W. Fairbanks, W. A. Goodyear,

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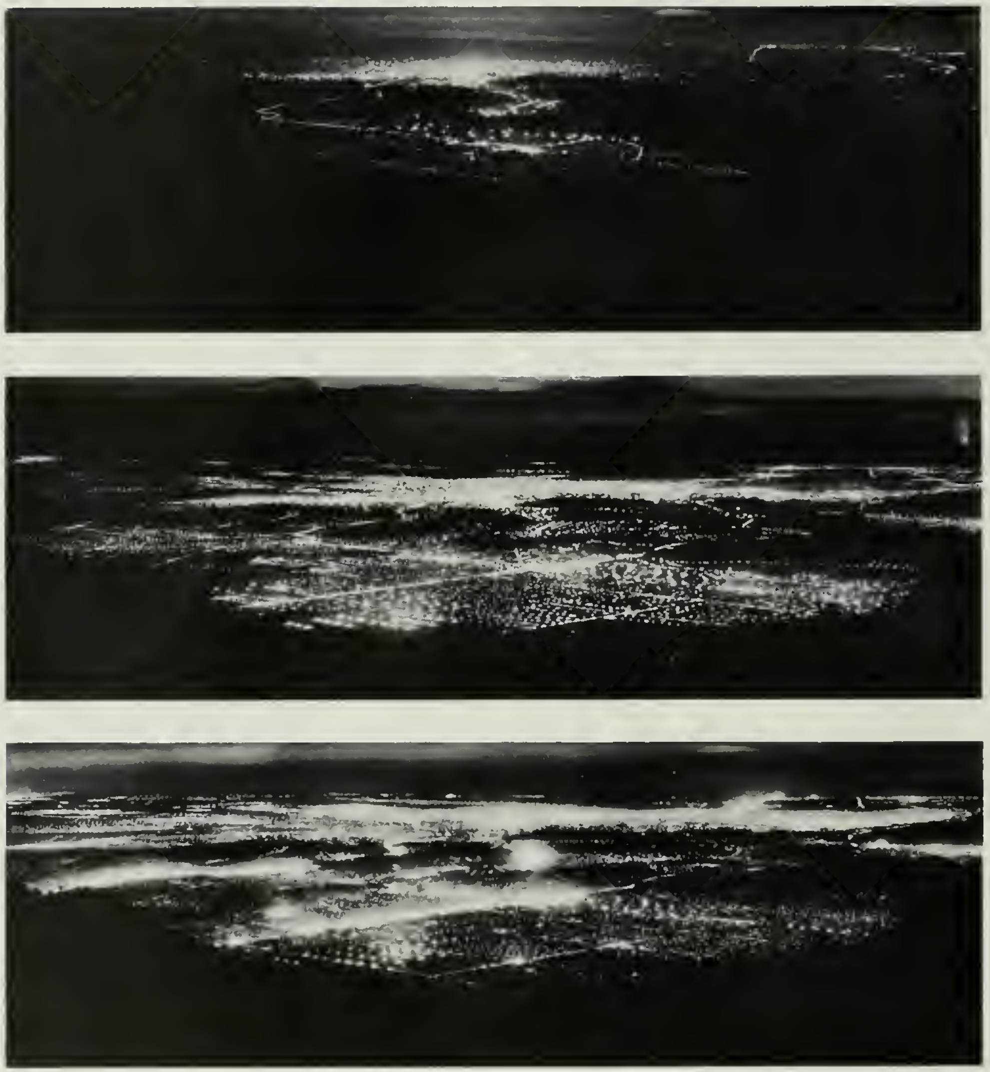

Figure 1. The growth of Los Angeles and neighboring cities during a 20-year period, as revealed by nighttime views southwestward from Mt. Wilson, in the San Gabriel Mountains. Top, 1906; middle, 1918; bottom, 1925. Pasadena is in foreground, Los Angeles in middle distance, San Pedro at far left, and Venice and Santa Monica are at far right. *Photos courtesy of Mt. Wilson and Palomar Observatories.*

FIGURE 2. Nighttime view southwestward across a part of the Los Angeles basin from Mt. Wilson, 1950, showing elongate structural highs that trend northwestward as dark areas across the basin floor. Repetto Hills, parts of the Newport-Inglewood uplift, San Pedro Hills, and Catalina Island appear at successively greater distances in left-hand part of view, and the Baldwin Hills, which mark a more northwesterly part of the Newport-Inglewood uplift, are in right-center distance. *Photo courtesy of William C. Miller.*

F. J. H. Merrill, C. R. Orcutt, W. L. Watts, and several others. During the last quarter of the century, teachers and students from the University of California and Stanford University also contributed vigorously to the growing total of geological information. Joseph Le Conte, J. C. Branner, A. C. Lawson, J. C. Merriam, and J. P. Smith were among the leaders in this early work, in which attention was directed mainly toward geologic mapping and to stratigraphic, structural, mineralogic, and paleontologic studies.

Period of Intensive Geologic Investigations. The first half of the present century was a period of burgeoning population in southern California, especially in the coastal areas. From a city of about 100,000 persons, Los Angeles grew to a sprawling metropolis with a population of nearly 2,000,000 (figs. 1, 2), and the population of San Diego multiplied nearly 120-fold. Accompanying this remarkable growth were further expansion of agricultural activities and an impressive development of many industries. In a very fundamental way, these and other major trends affected the amount and the kinds of geological work that was done in the region.

A long-term dwindling of interest and activities in metal mining was overshadowed by rapidly increasing demands for petroleum and many of the industrial minerals. By 1948, when the annual value of mineral production in the State reached the billion-dollar level, nonmetallic commodities accounted for more than 95 percent of this total. Discoveries of new reserves of oil and gas were reflected in production rates that increased from a modest average of 12,000 barrels per day in 1900 to averages of 850,000 barrels per day in 1923 and 982,000 barrels per day in 1952. The value of petroleum and petroleum products, obtained chiefly from fields in southern California, was approximately $975 million in 1952, but even this output was not sufficient to meet all demands in the region. Similar production trends characterized many of southern California's industrial minerals, although in general the periods of maximum increase came at later times.

Geologic knowledge was applied directly to the search for oil and gas beginning about at the turn of the century, and within a few years detailed studies of stratigraphy and structure led to discovery and development of new fields, as well as to improved understanding of fields that had been found earlier on the basis of surface seepages. The general trend of investigations in petroleum geology is clearly shown in the published record, as the earlier and largely descriptive summary reports (e.g., Goodyear, 1888; Eldridge, 1903) were followed by a long series of detailed reports, mainly by members of the U. S. Geological Survey, outlining the results of intensive studies in specific areas and districts (e.g., Eldridge and Arnold, 1907; Arnold and Anderson, 1910; Arnold and Johnson, 1910; Pack, 1920; English, 1921, 1926; Kew, 1924; Hoots, 1931; Woodring, et al., 1932, 1940). The work of these men, and of numerous oil-company geologists, members of university staffs, and other investigators, provided a sound basis for further interpretations, as well as for the pursuit of many specific lines of investigation in large parts of the region.

The geologic study of several other nonmetallic materials, particularly the salines, evolved in a similar way, and intensive investigations have continued to the present time, especially in the interior parts of the region. The earlier work of many geologists (e.g., Gale, 1914, 1915, 1926; Hess, 1908, 1910; Noble and Mansfield, 1922; Noble, 1926, 1931; Schaller, 1930) not only outlined the major features of numerous widely distributed deposits, but yielded more general data that, combined with the results of several broad reconnaissances (e.g., Ball, 1907; Knopf, 1918; Ellis and Lee, 1919; Brown, 1923; Thompson, 1929), formed the necessary background for later detailed studies. Of similar broad value were several other investigations that dealt in large part with metalliferous deposits (e.g., Harder, 1912; Hewett, 1931, 1954).

Beginning with those early days when the modest needs of the pueblo of Los Angeles were met by the Zanja Madre, or "Mother Ditch," and when streams and shallow wells supplied other settlements, the development of southern California's water resources was marked by a steadily expanding search for underground supplies. As the country became more populous, many of these supplies were found to be less than adequate, and the year 1913 marked the beginning of large-scale importations of water into some areas. In the meantime, geologic and hydrologic studies of both surface and underground supplies were made by the U. S. Geological Survey (e.g., Schuyler, 1896-1897; Mendenhall, 1905, 1908, 1909; Lee, 1912; Waring, 1919, 1921), and in later years by other organizations, as well. During recent decades, problems of water budgeting, natural and artificial recharge, and contamination have been added to those of water occurrence, and some of the latest studies of these problems have involved impressive syntheses of stratigraphic, structural, and geochemical data (e.g., Eckis, 1934; Upson, 1951; Piper, et al., 1953).

Residents of southern California have been painfully aware of earthquakes and related phenomena since the days of earliest settlement, and for more than fifty years the relations between earthquakes and faults in the region have received geological attention. From the times when features that were formed along the trace of the San Andreas fault by the Fort Tejon shock of 1857 were described by Schuyler (1896-1897, pp. 711-713) and Fairbanks (Lawson, et al., 1908, pp. 43-45), attempts have been made to analyse southern California earthquakes in terms of their geologic causes and effects, and to solve the exceedingly difficult problem of earthquake prediction. The distribution, timing, and nature of fault movements and the elastic waves generated by them have been studied by means of increasingly detailed field observations, geodetic investigations, and the recording and analysis of seismic data obtained with a growing variety of instruments. The recent Arvin-Tehachapi (Kern County) earthquake in the southern end of the San Joaquin Valley (Benioff, et al., 1952; Buwalda and St. Amand, 1952) involved a series of shocks that probably has been more thoroughly and accurately recorded than any other in history, and a summary report on this earthquake is in press (1954) as Bulletin 171 of the State Division of Mines.

The value of geologic knowledge as applied to the location, design, and construction of engineering works has been increasingly recognized in southern California during recent years. The collapse of the St. Francis dam and its tragic consequences (Ransome, 1928), the effects of numerous floods (e.g., McGlashan and Ebert, 1918; Troxell and Peterson, 1937; Troxell, et al., 1942) and earthquakes (see Richter, Contribution 1, Chapter X, this volume), and the more commonly recurring damage from landslides, subsidence, and other earth movements have prompted geologic investigations of many kinds.

The research activities of members of university staffs and many other investigators have spanned a host of problems, especially during recent decades, and a few have led to the mapping of large areas (e.g., Larsen, 1948; Dibblee, 1950). Some, in contrast, have involved much time in the laboratory, and have included paleontological, geophysical, and geochemical work. As these and the numerous other investigations in the region have become increasingly diversified in their nature and aims, and as the investigators themselves have represented a growing variety of interests and affiliations, attempts have been made to summarize the existing information and, in some instances, to make tentative interpretations. One of these attempts produced a summary of geologic features and their relations to earthquakes (Hill, 1928), and another yielded a useful guidebook that was published under the auspices of the U. S. Geological Survey (Gale, et al., 1932) for the Sixteenth International Geological Congress. Others, devoted mainly to the geology of the stratified rocks, resulted in publication of the classic volumes by Reed (1933), Reed and Hollister (1936), and Jenkins, et al. (1943). An excellent geologic map of the entire State was prepared by the State Division of Mines in 1938 (Jenkins, 1938), and currently is undergoing fundamental revision on the basis of newly available information. Data on minerals of the State have been assembled by Murdoch and Webb (1948), on mineral deposits by the staff of the State Division of Mines (1950), and on geomorphic features by Hinds (1952).

THE NATURAL PROVINCES

Southern California is a region of great topographic and geologic diversity. Included within its limits are high mountain ranges (figs. 8, 11) and valleys whose floors lie below sea level (fig. 5), precipitous canyons and broad basins at many levels (figs. 6, 8), and an assemblage of other physiographic features that reflect a complex geologic history and a wide variety of rock types and structural elements. The land of the region is readily divisible into eight natural provinces, in large part on the basis of distinctive physiographic characteristics, but more fundamentally on the basis of geologic history since middle Mesozoic time.

The physical divisions of southern California already have been described by Hill (1928, pp. 74-101), Fenneman (1931, pp. 373-379, 493-508), Reed (1933, pp. 1-26), Jenkins (1938), Hinds (1952, pp. 63-108, 145-229), and several others, and hence only a brief summary of outstanding geologic features is presented in the following paragraphs. The distribution, areal dimensions, and major topographic elements of the provinces are shown in figures 3 and 4.

Southern Coast Ranges. The southern part of the Coast Range province is characterized by a topographic and structural grain that trends northwest to north-northwest. A thick section of upper Mesozoic and Cenozoic sedimentary rocks, mainly marine and mainly clastic, is exposed over most of the area. These strata rest upon, or are in fault contact with, mildly metamorphosed but intricately deformed rocks of the Jurassic (?) Franciscan group, which include sandstone, conglomerate, shale, chert, limestone, various schists, basalt, diabase, and associated basic intrusive rocks that have been largely altered to serpentine.

The province is sliced almost longitudinally by two major fault zones, the San Andreas on the northeast and the Nacimiento on the southwest (fig. 12), as well as by many other subparallel breaks with northwesterly trend. Partly exposed in the block between the two main faults is a core of plutonic rocks, chiefly quartz diorite and granodiorite of probably Mesozoic age. This block appears to have been a highland mass during much of Tertiary time, while sediments were being deposited in the flanking areas. Tertiary deformation, especially in middle Miocene, upper Pliocene, and mid-Pleistocene times, is reflected by numerous folds, faults, and unconformities in the sedimentary section.

San Joaquin Valley. The San Joaquin Valley, or southern part of the Great Valley of California, is an immense, nearly flat-floored plain that is largely covered by alluvium. It was an important basin of Cenozoic deposition, and beneath its floor is a remarkably thick

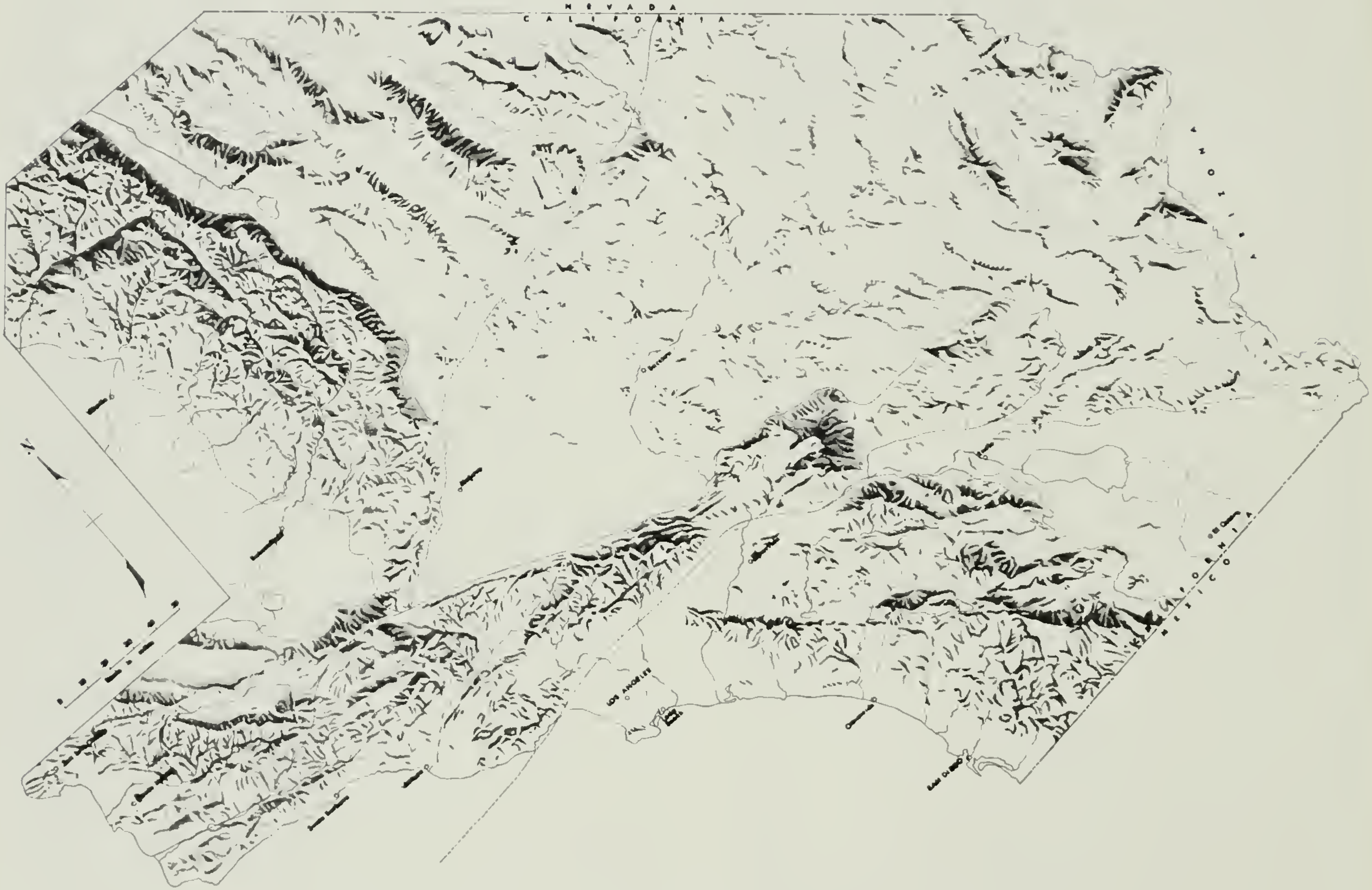

FIGURE 3. Map showing the major topographic features of southern California. Dashed lines are generalized boundaries of the natural provinces.

FIGURE 4. Map showing the natural provinces of southern California, with names of the principal features shown in figure 3.

FIGURE 5. View eastward at the steep, fresh fault scarp of the Black Mountains, with the floor of Death Valley in foreground. The strikingly symmetrical alluvial fan heads at the mouth of Coffin Canyon, an extremely narrow and precipitous gorge that gives way upstream into somewhat more open country. *Photo by J. S. Shelton and R. C. Frampton.*

and varied section of dominantly clastic sedimentary rocks. More than 25,000 feet of Upper Cretaceous marine strata is overlain by as much as 40,000 feet of younger formations that include both marine and nonmarine strata, as well as some volcanic rocks of basic and intermediate composition.

The broad trough of sedimentary deposits is asymmetric, with a relatively steep westerly flank and a gently inclined easterly flank that lies upon the western part of the Sierra Nevada fault block. During much of Tertiary time this basin was occupied by an inland sea, and a variety of lithologic facies accumulated contemporaneously as its floor continued to subside (Hoots, et al., Contribution 8, Chapter II, this volume). Several episodes of uplift and depression are attested by unconformities and by lithologic contrasts within the sedimentary section, and many open folds, developed chiefly in mid-Pleistocene time, are present in both the marginal and interior parts of the basin. Several prominent lines of folding project southeastward and east-southeastward into the valley from its western margin, and relatively severe deformation in the southern end and along the western side of the valley is expressed by numerous thrust faults and overturned sections of stratified rocks.

Sierra Nevada. The southern part of the Sierra Nevada proper is fundamentally a huge, asymmetric, westward-tilted block that is bounded on the east by a zone of high-angle faulting and disappears to the west beneath the sedimentary rocks of the San Joaquin Valley. This block consists mainly of plutonic rocks that represent the composite Sierra Nevada batholith of Mesozoic age, together with older metamorphic rocks that appear in most areas as inclusions, roof pendants, and screens in the igneous terrane. Resting upon these crystalline rocks are scattered patches of lower Tertiary fluviatile sediments, as well as Tertiary and Quaternary volcanic rocks. Pleistocene glaciation has left its stamp on the landscape within the range, and glacial deposits are widespread.

The Tehachapi Mountains, at the south end of the province, differ from the Sierra Nevada proper in several important respects. Although they consist mainly of the same kinds of pre-Cenozoic rocks, they trend northeast, are bounded on both sides by major fault zones, and appear to have a much more complex internal structure. Within the range are large masses of Tertiary nonmarine strata and associated volcanic rocks, and along its margins are moderately to steeply tilted sections of Tertiary rocks. Both the Tehachapi Mountains and the Sierra Nevada appear to have been affected by several episodes of uplift during Cenozoic time, and the most recent and possibly greatest of these took place in Pleistocene time.

Basin-Range Province. The part of the Basin-Range province that lies in southern California is characterized by north-trending ranges, intervening valleys and basins, and an interior drainage. The geologic section is very complex, and includes earlier pre-Cambrian gneisses and plutonic rocks; several thousands of feet of younger pre-Cambrian sedimentary rocks and diabase; as much as 17,000 feet of clastic and carbonate strata of Cambrian age; assemblages of younger Paleozoic strata, of even greater aggregate thickness, in which carbonate rocks are abundant; Mesozoic sedimentary and volcanic rocks; widespread plutonic rocks of Mesozoic age; fluviatile and lacustrine sedimentary strata that appear to have been deposited during various parts of the Cenozoic era, mainly in separate basins; and widely scattered volcanic and intrusive rocks of Cenozoic age. Not all of these rocks ordinarily are present in any single area.

Many of the ranges are essentially fault blocks, and some of the valleys are fault-bounded troughs, but neither the structural pattern nor the history of deformation in the region is at all simple. Indeed, adjacent fault blocks commonly have had distinctly different geologic histories, thanks mainly to the nature and timing of movements on the faults that separate them. The province is in part bounded on the south by the Garlock fault zone (fig. 7), along which there has been much left-lateral movement, and it is bounded on the west by the Sierra Nevada fault zone, along which dip-slip movement probably has been dominant. Within the province are many other high-angle faults, as well as flat to moderately-dipping thrust faults, and in general faulting has been the dominant expression of tectonic activity.

The effects of late Mesozoic and Cenozoic deformation are exposed in most parts of the region, and widespread Quaternary faulting and warping is reflected by many elements of the present topography. Impressively fresh fault scarps (fig. 5), scarplets and small grabens in alluvial-fan deposits (fig. 6), aligned ridges and trenches on several valley floors (fig. 7), and hogback ridges of tilted and folded Pleistocene deposits are typical examples. Also preserved in several of the basins are shoreline and outlet features of Pleistocene and early Recent lakes (fig. 7) that at least once were parts of an integrated system of drainage.

Mojave Desert. The Mojave Desert region, most extensive of the natural provinces, is in large part a gigantic fault-bounded wedge that points westward. It consists of pre-Cambrian gneisses, plutonic rocks, and severely deformed and metamorphosed sedimentary rocks; sections of Paleozoic stratified rocks that have been metamorphosed to various degrees; scattered sedimentary, metasedimentary, and metavolcanic rocks of Mesozoic age; a considerable abundance and variety of Mesozoic intrusive rocks; and middle and upper Cenozoic

Figure 6. The Wildrose graben and a part of the Panamint Range, as viewed south-southeastward from a point above Panamint Valley. The graben was developed across a series of Quaternary alluvial fans, and beheaded much of the drainage in the area at right. Much of the visible mountain area is underlain by stratified rocks of Cambrian and pre-Cambrian age. *Photo by J. S. Shelton and R. C. Frampton.*

FIGURE 7. The Garlock fault zone, as viewed east-northeastward from a point over the southwestern corner of the Searles Basin. Note the fresh scarps and the elongate trench, the deepest part of which is marked by a small playa. Shoreline features of a lake that occupied the Searles Basin during a part of Pleistocene time are clearly visible in left foreground. The Slate Range is in near distance, and in extreme distance beyond is Charleston Peak, in Nevada. *Photo by J. S. Shelton and R. C. Frampton.*

FIGURE 8. View northward at the bold south face of the San Gabriel Mountains, here interrupted by San Antonio Canyon. San Antonio Peak is in distance, and Ontario Peak is nearer and at right. *Pacific Air Industries photo.*

igneous rocks and sedimentary strata that were deposited mainly in separate basins.

Younger pre-Cambrian sedimentary rocks like those in the Basin-Range region to the north have been recognized only in the northern corner of the Mojave Desert province. No lower Paleozoic strata have been identified in the central and western parts of the province, although they may be present as metamorphic rocks in some areas. In general, fossiliferous sections of unmetamorphosed pre-Cenozoic rocks are common in the northeastern part of the region only, and with few exceptions the stratigraphic relations become progressively more obscure to the west and south. The province was subjected to widespread erosion from late Mesozoic to middle Tertiary time, and, unlike the regions to the north, south, and west, it contains no Lower Tertiary sedimentary rocks (Hewett, Contribution 1, Chapter II). Younger fluviatile and lacustrine sediments indicate a complex history of basin formation that began in middle Miocene time and continued to the present.

Much of the province lies between the left-lateral Garlock fault on the north and the right-lateral San Andreas fault on the southwest (fig. 12). Within the province are north- to northeast-trending folds, steeply dipping faults, and some major thrust faults of middle Jurassic to late Cretaceous age, as well as more open folds, low-angle thrust faults, and steeply dipping faults of late Cenozoic age. Many of the high-angle faults trend northwest (fig. 12) and show evidence of recent movement. Igneous activity in the region is represented mainly by pre-Cambrian and Mesozoic plutonic rocks, pre-Cenozoic volcanic and metavolcanic rocks, and Cenozoic volcanic and hypabyssal intrusive rocks.

Transverse Range Province. Trending essentially east-west across the regional grain of southern California is the Transverse Range province, which comprises elongate mountain ranges and valleys, chains of hills, and broad basins that are geologically very complex. Its eastern half, which includes much high and mountainous country (figs. 8, 11), is composed mainly of Mesozoic plutonic rocks, older metamorphosed sedimentary and volcanic rocks that are at least in part of Paleozoic age, and some igneous and metamorphic rocks of pre-Cambrian age. Tertiary sedimentary rocks, both nonmarine and marine, are preserved locally. The western half of the province is featured by diverse sections of Tertiary sedimentary rocks, in places enormously thick, that were deposited in several large basins (fig. 9). These and associated volcanic rocks rest upon and against older sedimentary rocks, as well as still older crystalline rocks that are in part correlative with those exposed in areas farther east.

The province as a whole resembles the adjoining Coast Range and Peninsular Range regions in several respects, but is distinguished from them by prevailing east-west structural trends. Elongate, generally steep-sided folds, many of which have been ruptured along their axes or on one or both flanks by gently to steeply dipping compressional faults, are characteristic of the basinal areas and those western ranges that consist mainly of sedimentary rocks (fig. 9). The other ranges are best regarded as great upthrown blocks, bounded in part by faults that dip very steeply and have had large strike-slip, or lateral, components of movement, and in larger part by reverse faults that appear to converge downward beneath the blocks. The great San Andreas-San Jacinto fault zone slices across the eastern part of the province at an acute angle, and the San Gabriel fault zone is somewhat similarly disposed farther west (fig. 12).

Several episodes of intense deformation, including a late Mesozoic orogeny and accompanying widespread plutonic intrusion, are recorded by the older rocks. The Cenozoic section contains unconformities, some of them extensive, that reflect a variety of disturbances in both basin and source areas. The great mid-Pleistocene orogeny produced intense folding and uplift, and was responsible for development of the major elements of the present topography, including a number of impressive scarps (fig. 8). Marine terraces of Pleistocene age are prominent features of the coastal landscape, and lie at elevations of as much as 1,200 feet above sea level. Some of them have been warped and broken by faults.

Colorado Desert. The Colorado Desert is an elongate, low-lying depression whose alluviated floor is separated from the Gulf of California by the delta of the Colorado River and is in part occupied by the Salton Sea. It marks the site of a former basin of middle and late Cenozoic sedimentation, and a thick section of fine- to very coarse-grained, dominantly nonmarine strata, together with some volcanic rocks, is exposed in its marginal parts. This section rests upon igneous and metamorphic rocks of pre-Cenozoic age in some areas, and is in fault contact with them in others. The northeast side of the province is traversed longitudinally by several subparallel breaks of the San Andreas fault zone, and its highly irregular western margin is in part outlined by the Elsinore, San Jacinto, and other major fault zones that trend northwest (fig. 12). Many of the faults cut and offset rocks that are as young as Quaternary.

Most of the sedimentary rocks were laid down as alluvial-fan and lacustrine deposits, but included in the sequence are marine beds that accumulated in a shallow, northward-extending arm of the Gulf of California during lower Pliocene time. The most recent history of the basin involves subsidence, local volcanic activity, intermittent movements along faults in both the marginal and interior areas, and occupation by at least one large fresh-water lake, perhaps as recently as a few hundred years ago.

FIGURE 9. The Ventura River Valley, Ojai Valley, and adjacent mountains, viewed northeastward from a point about 6 miles north of Ventura. A thick section of Miocene and Pliocene strata is exposed in the Ventura Hills and on Sulphur Mountain, in foreground and central part of view, respectively. Eocene strata are prominent on the face of the Topatopa Mountains, in distance beyond Ojai Valley, and older rocks form most of the mountains in far distance. *Photo by Erickson, 1931.*

Peninsular Range Province. The Peninsular Range province is characterized by a northwest-trending topographic and structural grain that butts abruptly against the Transverse-Range grain on the north. The inland parts of the province include several high mountain ranges (figs. 10, 11), and are underlain chiefly by igneous, metasedimentary, and metavolcanic rocks of Paleozoic and Mesozoic age. The igneous rocks include widespread representatives of the great composite southern California batholith. Patches of younger volcanic rocks and nonmarine sediments of middle and late Cenozoic age are present locally.

A coastal plain of irregular outline is marked by numerous marine terraces. It is underlain by dominantly clastic marine and nonmarine strata of Upper Cretaceous, Tertiary, and Quaternary age, as well as by scattered volcanic rocks of Tertiary and Quaternary age. This section thickens to as much as 40,000 feet in the Los Angeles basin (fig. 10), at the north end of the province, where it evidently accumulated in a subsiding area under widely varying conditions of sedimentation. In many respects this basin resembles other Tertiary basins in the adjoining Transverse Range province, but its major structural features have the characteristic Peninsular Range trend.

The offshore area, or continental borderland, commonly is included in the Peninsular Range province. It is distinguished by prominent, steep-sided ridges that appear to be horst-like in structure, and by intervening depressions that in general have the form of closed basins (Emery, Contribution 7, Chapter II). The ridges are composed mainly of foliated rocks that resemble the Franciscan formation of the Coast Ranges to the northwest, and in places are covered with sedimentary and volcanic rocks of Tertiary age. Younger sediment also veneers the ridges, and forms considerable thicknesses of fill in the basins.

The entire province can be regarded as an uplifted and westward tilted plateau that has been broken into several large, elongate, subparallel blocks by major faults that trend northwest (fig. 12). Most of these faults have been intermittently active during large parts of Cenozoic time, and adjacent fault blocks commonly have had distinctly different histories. The sedimentary sections have been folded along axes that trend west-northwest to north-northwest. Most of the large folds are open, with undulatory crests and troughs that in some areas have affected the accumulation of oil (fig. 10), and many are complicated by unconformities and small-scale wrinkling. Some of those in the Los Angeles basin were developed so recently that their distribution and form are plainly reflected by the present topography (figs. 2, 10).

CURRENT GEOLOGIC PROBLEMS

In the preface to his volume on the geology of California, Reed (1933, p. VII) pointed out the need for increased consideration of broad problems with the following apt remarks:

> "The last thirty years have thus contributed a supply of accurate data of the type needed for an adequate interpretation of the problems of regional geology and geologic history. During this period, however, relatively less attention than formerly has been given to the broader aspects of these problems. California geology has thus come to seem more complex, disconnected, and chaotic than ever before. In recent years some geologists have even entertained the idea that the State is really nothing but a great series of separate structural blocks, each with an independent history since some stage of the Mesozoic at least. The adoption of any such hypothesis would apparently make hopeless an attempt to write an account of regional geology or general geologic history. In order to keep this disintegrative tendency within bounds, and also to see the problems of special districts in their broader relations, there seems to be a need for attempted synthesis like that presented in this paper."

That many geologists are aware of a renewed need for summation and synthesis of available data is implicit in the preparation and publication of the present volume. Even though the ''disintegrative tendency'' of 20 years ago may have been more apparent than real, the theme of adjacent fault blocks with contrasting—albeit neither independent nor unrelated—histories is founded upon such widespread and compelling evidence that it cannot be ignored. It poses some formidable problems of correlation and integration, to be sure, but their solution will be fundamental to ultimate elucidation of southern California's geologic history.

Many of the problems that are discussed in the following contributions to this volume are common to more than one fault block or to more than one general province, and some of them are treated on a regional basis in at least 21 of the contributions. The ratio of known questions to wholly satisfactory answers still is provokingly high, but the outlook for its net reduction seems to be far from discouraging. A brief and incomplete sampling of current problems, not including solutions thereto, is presented in the remainder of this paper.

Pattern of Major Faults. As fault maps of southern California are improved in the light of new data, and as the significant elements of the pattern are more fully recognized, attempts to interpret these elements in genetic terms are still confronted by the need for additional information on the nature and timing of fault displacements, and on the directions and amounts of net slip. These factors are difficult to determine under any but the most favorable conditions, and the problem is compounded by evidence of reoriented movements along numerous recurrent faults.

The compilation in figure 12 shows most of the known major faults in a large part of southern California. Nearly all of these have been active during parts of Cenozoic time, and some date back at least to

FIGURE 10. View eastward across a part of the Los Angeles basin, showing the Long Beach oil field as it appeared in 1932. The field marks the general position of the Newport-Inglewood uplift in this area. Signal Hill is at right, in the more distant part of the field, and Santiago Peak, in the Santa Ana Mountains, is at center on the skyline. *Photo courtesy Fairchild Aerial Surveys, Inc.*

mid-Mesozoic time. Especially prominent among them are the San Andreas, Garlock, Nacimiento, San Gabriel, San Jacinto, and Elsinore faults, all steeply dipping, deep-rooted, long-active breaks on which strike-slip, or lateral, movements amounting to miles or even tens of miles have taken place. These major breaks pose several problems that are discussed in Chapter IV and elsewhere in the published record (e.g., Crowell, 1952; Hill and Dibblee, 1953; Noble, 1954; Wallace, 1949), and it is interesting to note that, even for the faults that have been studied in painstaking detail, the most reliable estimates of net slip are based upon indirect evidence or upon a summation of several compatible lines of suggestive, but not conclusive, evidence. Only a few rock units or other features can yet be correlated with confidence across any of these faults, and unfortunately net slip rarely is measured by the separation indicated on a geologic map or section.

Thrust faults and high-angle reverse faults are common in the region southwest of the San Andreas fault, whereas major normal faults are very rare. In the country to the northeast, however, both normal and other types of dip-slip faults are present. Hill (Contribution 1, Chapter IV) has attempted to correlate the directions and amounts of displacement along the major lateral, reverse, and thrust faults with a primary pattern of deformation, and has thereby deduced a regional strain pattern of north-south shortening. Although admittedly over-simplified, especially with respect to timing of movements, this is an imaginative and stimulating application of the data now available. Hewett (Contribution 2, Chapter IV) has interpreted the regional pattern of faulting in the Mojave Desert province, and has performed a real service in correlating the fault movements with numerous other events in the geologic record.

The relations between the San Andreas fault system and the faults in structurally high parts of the Transverse Range province invite speculation on the history of movements. In the southern Coast Ranges the San Andreas fault zone is a relatively narrow and well-defined master break that trends southeast. It bends sharply eastward before reaching the area of junction with the Big Pine and Garlock faults, and thence cuts across the Transverse Ranges in an east-southeastward direction (fig. 12). Along the northern edge of the San Gabriel Mountains it splits into two major fault zones, the San Andreas and the San Jacinto. Farther eastward, along the south side of the San Bernardino Mountains, the San Andreas zone is involved in a complex way with east-trending faults of the Transverse Range system, as shown by Allen (Map Sheet No. 20), and it differs in several important respects from its more northwesterly segments. It seems probable that a substantial part of the total displacement along these more northwesterly segments is represented to the southeast by displacements along the San Jacinto fault zone.

The Elsinore fault zone, which lies on the southeastward projection of the Coast Range segment of the San Andreas fault zone, may well be related in a similar way. Perhaps the ancestral San Andreas fault was deflected eastward by the great mass of the Transverse Ranges, and some of its older segments were converted into parts of the reverse faults along which the Transverse Ranges were uplifted. The interplay of movements probably was very complex in both space and time, and the present San Andreas and San Jacinto fault zones almost certainly displaced many of the Transverse Range breaks. The many pieces of this puzzle are even more difficult to assemble than those in the area where the San Andreas and Garlock faults meet (Hill and Dibblee, 1953), and solution of the general problem must await detailed mapping and interpretation of the crystalline rocks in a very large area.

Deformation and Metamorphism of the Older Rocks. Most of the pre-Cretaceous rocks exposed in southern California show the effects of at least one episode of deformation and metamorphism that antedated the sequence of severe deformation recorded by many of the younger rocks. So complex are most of the end products, however, that few investigators have attempted to decipher their earlier structural history. Several of the principal difficulties of interpretation have been summarized for the Mojave Desert region by McCulloh (Contribution 2, Chapter VII), and the problems are still more troublesome in areas farther west and southwest, where the older geologic record is even less well known.

Pre-Tertiary thrust faulting is recorded from several areas (e.g., Hewett, 1931, pp. 42-55; Noble, Contribution 5, Chapter IV), and ancient folding and high-angle faulting have been noted from numerous areas in which the older rocks have been studied. Superimposed upon most of these features are the effects of younger deformation, which commonly include pervasive crushing, shearing, and even mylonitization. In some places massive crystalline rocks plainly have participated in the folding of overlying sedimentary strata (e.g., Hill, 1930, pp. 158-159; Dibblee, Contribution 2, Chapter II). Additional descriptive information, supplemented by careful studies of rock fabric and structure in relation to tectonic environment (e.g., Weiss, 1954), must be at hand before the more general aspects of deformation in the older rocks of the region can be satisfactorily determined.

The problems of metamorphism also are complex, mainly because of difficulties in establishing the nature and timing of individual metamorphic effects. Some of the rocks may well have been metamorphosed prior to widespread intrusion of the Mesozoic plutonic

Figure 11. San Gorgonio Pass and the highest country in southern California, as viewed west-northwestward from the Coachella Valley in 1931. San Jacinto Peak (10,831 feet) is at left, San Gorgonio Mountain (11,485 feet) is at right, and San Antonio Peak (10,080 feet) is in center distance. These peaks represent the San Jacinto, San Bernardino, and San Gabriel Mountains, respectively. Palm Springs is in center foreground. *Photo courtesy Fairchild Aerial Surveys, Inc.*

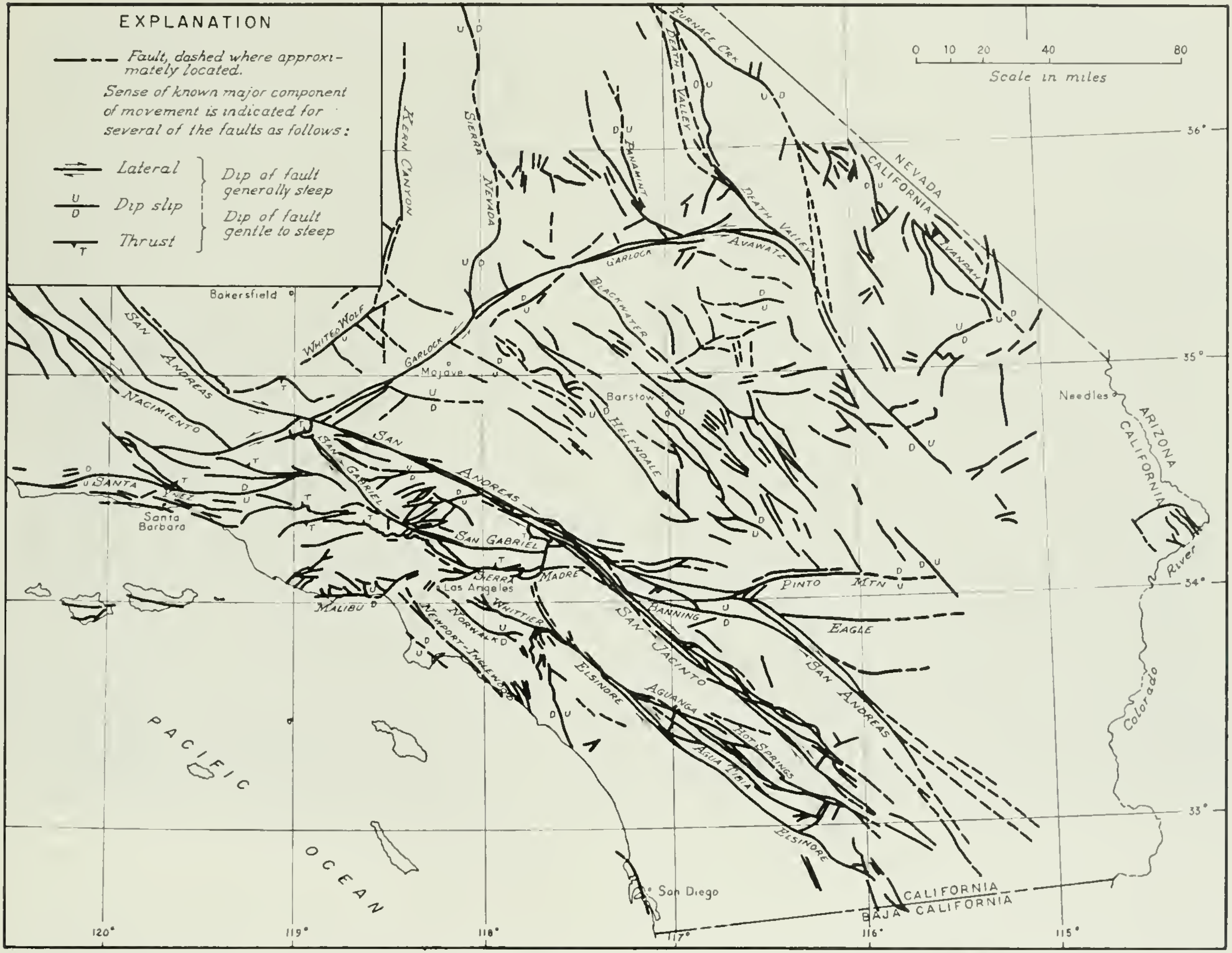

FIGURE 12. Map showing major faults in a large part of southern California. Based mainly on mapping and compilation by C. R. Allen, T. L. Bailey, T. W. Dibblee, Jr., D. F. Hewett, R. H. Jahns, and L. F. Noble.

FIGURE 13. Large shattered mass of gneissic hornblende diorite, at least 150 feet in maximum dimension, that lies wholly within a section of Pliocene sedimentary strata near the south end of the Avawatz Mountains, San Bernardino County.

rocks (e.g., Fraser, 1931, pp. 506-508; Larsen, 1948, pp. 32-36), and some of them assuredly have undergone subsequent contact metamorphism. Some of the pre-Cambrian rocks may well have been metamorphosed three times or more. The present net effects of metamorphism in rocks of like age are known to vary considerably, and commonly abruptly, from one area to another, but much more information is needed to establish the regional trends in metamorphic intensity, as well as the nature and mechanism of material transfer during the different episodes of metamorphism.

Paleozoic and Mesozoic Sedimentation. The general distribution of sedimentary basins and facies during Paleozoic and Mesozoic time is becoming well known for the Great Basin region of Nevada and eastern California, and it seems increasingly likely that some of the trends can be projected southward and southwestward in southern California. Despite the spotty exposures of these older rocks in much of southern California, as well as their varying degrees of metamorphism, near-lack of diagnostic fossils, and large-scale displacements by faulting, the little work done thus far on sedimentary facies already has yielded encouraging results. Indeed, it may prove to be one of the best approaches to the dating of some of the rocks, and even to the ultimate evaluation of major fault movements in the region.

Age and Correlation of the Mesozoic Plutonic Rocks. Plutonic rocks of Mesozoic age can be traced almost continuously from the Baja California peninsula northward to the central Sierra Nevada, and in general they represent two huge composite batholiths. The southern California batholith, which underlies most of the Peninsular Range province, is thought to be early Upper Cretaceous in age, mainly on the basis of relations in northern Baja California between fossiliferous sedimentary rocks and several plutonic masses that are regarded as parts of the batholith (Böse and Wittich, 1913; Woodford and Harriss, 1938). In contrast, the Sierra Nevada batholith is thought to be of late Jurassic age on the basis of stratigraphic evidence (Knopf, 1929, p. 14; Hinds, 1934). Some plutonic rocks in the Mojave Desert region have been assigned a Jurassic age, whereas others are regarded as post-Middle Cretaceous (Hewett, Contribution 1, Chapter II). Age assignments for the Mesozoic plutonic rocks in the areas between the Peninsular Ranges and the Sierra Nevada appear to reflect the preferences of individual geologists for correlations with one major batholith or the other.

Geochemical determinations of age have yielded estimates that range from 100 million years (Larsen, et al., 1952) and 110 million years (Ahrens, 1949, p. 250) to as much as 147 million years (Davis and Aldrich, 1953, p. 380) for the southern California batholith; about 100 million years for the Sierra Nevada batholith (P. C. Bateman, personal communication); 150 and 155 million years for two pegmatite bodies associated with plutonic rocks in the Mojave Desert region (Hewett and Glass, 1953); and an average of about 100 million years for several plutonic masses in the Transverse Range province (G. J. Neuerburg, personal communication). These represent a range from Middle Jurassic to Middle Cretaceous. Most of the estimates are regarded as accurate to the nearest 10 percent, but the discrepancies among the results obtained from different methods suggest that further refinements are needed before determinations of absolute age can be used for the more exact correlations that are desired.

As Woodford (1939, p. 258) points out, "If the southern batholiths are really mid-Cretaceous, a puzzling problem arises . . . Where does the Cretaceous pluton end and the Jurassic . . . one begin? Is it possible that the Sierra Nevada pluton was also intruded in mid-Cretaceous time?" Further, if the stratigraphic evidence in Baja California can be accepted, the southern California batholith must have been emplaced, cooled to solidification in at least its upper portions (see Larsen, 1945), in part unroofed by erosion, and then covered by marine sediments—all during Upper Cretaceous time!

Deposition and Life in the Tertiary Basins. The rocks and faunas of the Tertiary basins of deposition, and especially those in the coastal region, probably have received more detailed attention than any other major element of southern California geology (see Chapters II, III, and IX of this volume). Only a part of what is known has been published, however, and only a few recent attempts have been made to summarize the results of work done to date (e.g., Woodford, et al., Contribution 5, Chapter II; Durham, Contribution 4, Chapter III). Exciting possibilities remain for further integration of data on tectonic environment, mechanics and chemistry of sedimentation and lithification, paleoecology, and basin-sediment deformation with the wealth of available surface and subsurface information on thickness, lithology, and faunal relationships.

The western part of the Transverse Range province appears to be a particularly inviting area for further study. Thick, well-exposed, and carefully studied sections provide an almost unique opportunity for correlation of environments and processes in three adjoining, and at times interconnected, basins of dominantly marine, lacustrine, and fluviatile deposition, respectively. Farther east and northeast, in the Mojave Desert region, are nonmarine basins of Cenozoic deposition in which the occurrence of salines and associated clastic deposits still raises important questions of genesis. Happily, many of these questions are being addressed at the present time as part of a vigorous program of investigations by the U. S. Geological Survey.

FIGURE 14. Massive layer of chaotic breccia, about 40 feet thick, within a section of Plio-Pleistocene alluvial-fan deposits in lower Emigrant Canyon, Panamint Range. The layer consists mainly of dolomite fragments about 2 inches in average diameter, and is underlain by a thin layer of bluish gray schist-bearing breccia.

Chaotic Breccias. Masses of breccia that are best described as chaotic are present in nearly all parts of southern California, and are especially abundant in the Basin-Range, Mojave Desert, Colorado Desert, and Transverse Range provinces. They appear within sections of Cenozoic nonmarine strata or rest directly upon older rocks, and their spatial relations to the associated rocks are not everywhere clear. Some of these breccias consist of rock fragments that commonly are less than a foot in diameter, but others are much coarser, and contain disordered masses of rock whose maximum dimensions are measured in tens and even hundreds of feet (fig. 13). Many of the breccias are essentially monolithologic, and others are lithologically heterogeneous.

A sedimentary origin is readily deduced for most of the breccia masses that are interlayered or intertongued with finer-grained strata (fig. 14), and they appear to have accumulated as mud flows and debris flows. The origin of others, including most of those that contain gigantic fragments of rock and have been termed "chaos," is much less clear. These giant breccias are most abundant in the interior parts of the region, where they have been studied by Noble (1941), Hewett (1954), and many others. They have been variously interpreted as representing the disordered soles, tongues, or other parts of low-angle thrust faults, as deposits of composite thrust fault-sedimentary origin, or as deposits whose formation was associated with major high-angle faulting.

Whether wholly tectonic, wholly sedimentary, or of composite origin, most of these giant breccias seem to be related to large-scale faulting. Low-angle thrust faulting of very great net slip has been invoked to explain the occurrences of chaos in the southern Death Valley region (Noble, 1941; Curry, Contribution 7, Chapter IV), but recent work has shown that many of these breccia masses are of sedimentary origin and probably are more closely related to high-angle faulting (Noble and Wright, Contribution 10, Chapter 11). Much further study is needed to define accurately the respective roles of faulting and sedimentation, and of extensional and compressional faulting, in the development of these remarkable rocks.

Surfaces of Erosion. Broad surfaces of erosion are present in all of southern California's natural provinces, and appear at many different levels. Most of them were formed during the Quaternary period, and a few others seem to represent older surfaces that have been exhumed from beneath a cover of sedimentary or volcanic rocks. Although some of the surfaces are known to have been developed at different times, there has been considerable argument as to whether those in certain regions are remnants of much more extensive surfaces that were segmented and displaced by block faulting. It seems clear that even the most careful measurements of areal and vertical distribution of recognizable surfaces can serve as little more than a start toward resolution of this question, which is a particularly troublesome one in areas that are underlain by massive crystalline rocks.

Marine terraces, some of which have been deformed, are well preserved in the coastal areas. Their correlation, not only with one another, but with fluviatile terraces and broader surfaces of erosion farther inland, as well as with features of the offshore area, constitutes a formidable problem (e.g., Putnam, 1942; Upson, 1951; Sharp, Contribution 1, Chapter V). Solution of this problem will figure vitally in the reconstruction of Pleistocene and Recent events in the region, just as correlation of certain erosion surfaces already has contributed to an understanding of the Quaternary and late Tertiary history of the Mojave Desert region (Hewett, Contribution 1, Chapter II).

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