

9. GEOLOGY OF THE TEHACHAPI MOUNTAINS, CALIFORNIA*

By JOHN P. BUWALOA†

INTRODUCTION

The San Joaquin-Sacramento Valley, also known as the Great Valley of California, separates the Coast Ranges on the west from the Sierra Nevada on the east. The southern part of this major physiographic and structural province is about 50 miles in average width, and is terminated abruptly at its southeastern end by the Tehachapi Mountains, a range that trends roughly northeast. Uplifted principally by faulting, this mountain mass rises boldly (fig. 2) from the floor of the San Joaquin Valley—a floor so smooth and so extensive that in early days it was referred to as the San Joaquin Plains. The range also presents a rather straight and imposing, though somewhat less formidable, front toward the Mojave Desert to the southeast.

The alluviated surface of the San Joaquin Valley lies only a few hundred feet above sea level, whereas the surfaces of the extensive coalescing alluvial fans built out into the Mojave Desert by the intermittent streams that drain the southeast slopes of the Tehachapi Mountains stand at elevations of 2,500 to 3,000 feet above sea level. The general altitude of most of the mountain mass is 4,000 to 5,000 feet, but several ridges rise above 6,000 feet and the dominating peak of the range, Double Mountain, reaches nearly 8,000 feet about 7 miles south of Tehachapi.

For many years the Tehachapi Mountains were regarded simply as the southern end of the great rigid, westward tilted Sierra Nevada block, but their structure, geological history, and origin are entirely different from those of the Sierra Nevada. Topographically the Tehachapi Mountains are continuous with the Sierra Nevada to the northeast, and form a connecting link between that range and the Transverse Range province to the southwest. They did not originate as an unbroken fault block tilted toward the San Joaquin Valley, but instead resemble a broad horst with complicated internal structure and with complex fault structure along its margins.

The northwest and southeast sides of the Tehachapi Mountains are rather sharply set off from adjacent provinces, mainly by fault scarps, but the end boundaries are topographically rather indefinite. The San Andreas fault southeast of Tejon Pass, and Grapevine Canyon north of the pass, form an irregular but convenient south-west limit of the range. The northeast limit on some maps is taken at Tehachapi Valley and Tehachapi Creek, the general route of the

Southern Pacific Railroad and the Bakersfield-Mojave highway, but commonly included in the range is the mountainous country as far north as the south ends of Breckenridge Mountain, Walker Basin, and Kelso Valley. The northeast-southwest dimension of the range hence is roughly 50 miles, and its width increases from about 11 miles at the southwest end to about 30 miles at the indefinite northeast end.

Most of the range is in a semi-arid climatic belt that receives 10 to 20 inches of rainfall per year. The lower slopes and adjacent parts of the San Joaquin Valley and Mojave Desert are arid, and receive only a few inches of rainfall per year. The highest ridges and peaks, which constitute only a small fraction of the range, receive as much as 30 inches.

AREAL GEOLOGY

General Features

Upturned Tertiary formations crop out along both the northwest or San Joaquin Valley margin and the southeast or Mojave Desert margin of the Tehachapi Mountains, but more than 90 percent of the area of the range is underlain by pre-Cretaceous crystalline rocks (fig. 1). Some of these older rocks are metamorphic, but most are coarse-grained intrusive types. One area of Tertiary strata and associated volcanic rocks, several tens of square miles in extent, lies within the mountains northeast of Tehachapi Valley. These Tertiary strata, together with those exposed along the flanks of the range, shed much light on the later geologic history of the region and on the origin of the range. Unfortunately only a small fraction of the area has been mapped in detail, and hence no discussion of the geology can be made in more than general terms.

Pre-Cretaceous Sedimentary Rocks

Numerous patches of pre-Cretaceous metasedimentary rocks are scattered within the Tehachapi Mountains, but their aggregate outcrop area is only a small fraction of the total area of the range. They are well exposed on both the north and south sides of Tehachapi Valley, on the south side of the mountains about 9 miles west of Mojave and in areas farther west, and east of Tejon Pass, between Gorman and Lebec. They consist mainly of marbles, quartzites, slates, phyllites, and schists derived from both sedimentary and igneous rocks. The carbonate rocks have been burned for lime in the vicinity of Tehachapi during past decades, and are now being quarried for cement at Monolith.

* Contribution No. 693, Division of the Geological Sciences, California Institute of Technology.

† Professor of Geology, California Institute of Technology.

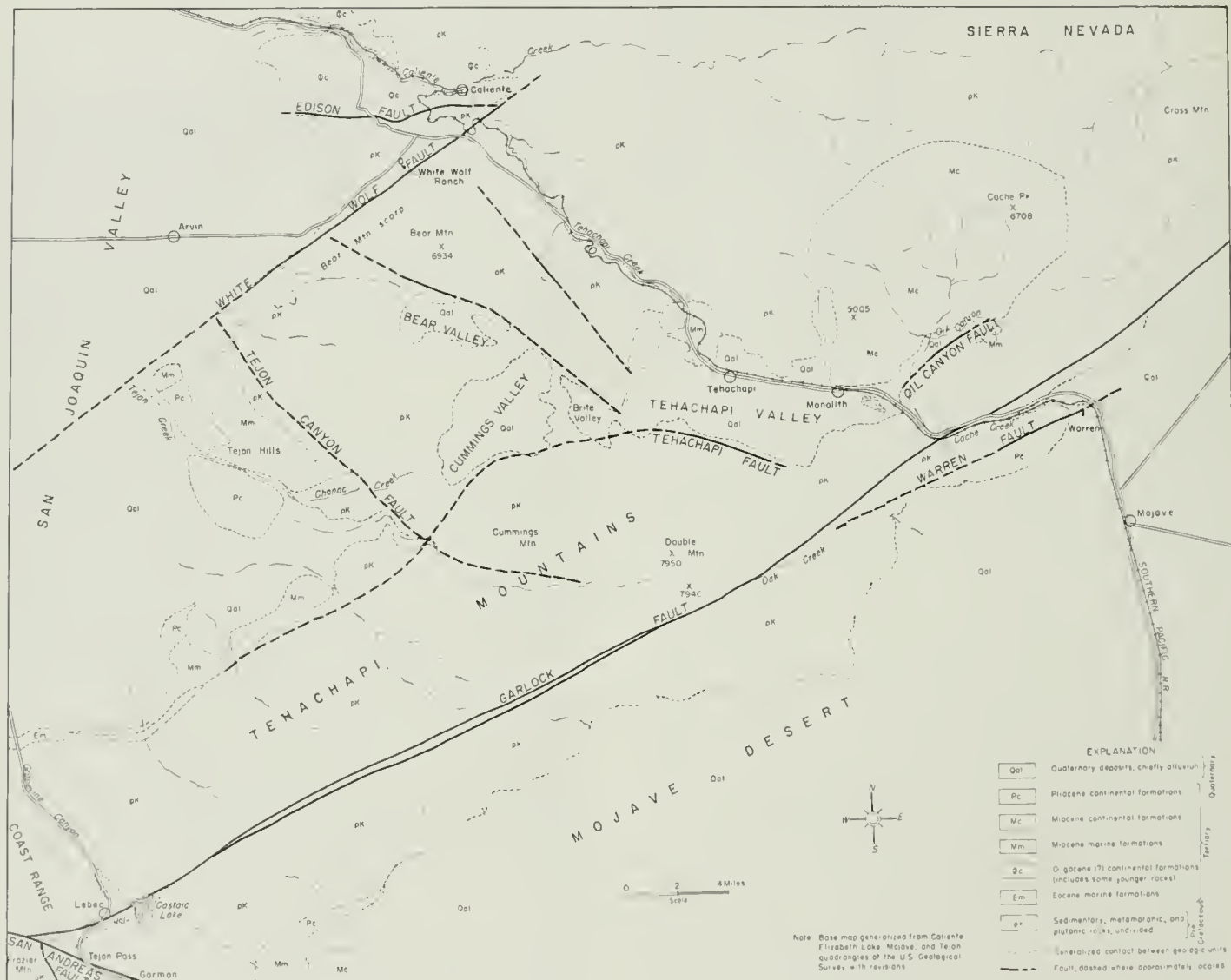


FIGURE 1. Geologic map of the Tehachapi Mountains.

The foliation in these metasedimentary and included igneous rocks ordinarily is parallel or nearly parallel to the bedding. The sedimentary section presumably corresponds to the Bean Canyon series of Simpson (1934) and to the Kernville series of Miller (1931) in the country farther north. On the basis of lithologic similarity, it has been considered as probably equivalent to the Calaveras formation of the middle Sierra Nevada, which usually is regarded as Carboniferous in age. Direct evidence of age of these beds in the Tehachapi Mountains consists only of supposed crinoid stems found by Goodyear (1888) on the south side of Brite Valley; they would indicate a Paleozoic or Mesozoic age.

The metamorphosed sediments occur in elongate patches as much as several miles in length, and with widths that generally do not exceed a mile or two. They commonly trend north to northwest. The strata themselves ordinarily strike roughly parallel to the long dimensions of the patches and dip at steep angles, but they are strongly deformed and commonly show small-scale folding, crumpling, and minor faulting. Thicknesses of several thousand feet can be measured, and the bodies clearly are remnants of a once-thick and important series of sedimentary formations that underlay the whole region; the remnants probably are mostly roof pendants.

Also present are scattered patches of still older metasedimentary rocks, mainly schists commonly associated with quartzites. One of the largest masses of these rocks is the strip of Pelona schist that lies between two branches of the Garlock fault and extends from a point near Lebec northeastward for a distance of more than 20 miles (Wiese, 1950). Its width is about 1 mile. These metasedimentary rocks are presumably pre-Cambrian in age.

Pre-Cretaceous Intrusive Rocks

By far the most extensive rocks in the Tehachapi Mountains are plutonic types of pre-Cretaceous age. They have not been studied exhaustively in any one district, but some general statements about them have been published by Goodyear (1888), Lawson (1904), Hoots (1930), Miller (1931, 1946), Simpson (1934), Miller and Webb (1940), Dibblee (1952, 1953), and others. For many years these intrusive rocks were thought to be a part of the great Sierra Nevada batholith, and to connect the old rocks of the Sierras with those of the Coast Ranges, but it now seems clear that, as in the Sierra Nevada farther north, the history of intrusion is far more complex than the emplacement of a single great molten body. The Tehachapi Mountains consist of numerous coarse-grained plutons of somewhat diverse mineralogical composition, of very irregular shapes and sizes, and of different ages.

Two general categories of older intrusive rocks can be recognized in the range. The younger of these includes the great bulk of the



FIGURE 2. View eastward at northwest face of Bear Mountain, with floor of San Joaquin Valley in foreground. The entire face consists of pre-Cretaceous crystalline rocks. The violent earthquake of July 21, 1952, originated on a reverse fault along base of this scarp; the fault displacement created numerous ground ruptures along the trace, involving offsets of as much as a few feet.

intrusives—rocks that range in composition from granite through monzonite, granodiorite, and quartz diorite to gabbro. The average composition is in the granodiorite range. These rocks are probably Jurassic in age, and correspond in general to the granodiorites of the Sierra Nevada. They are foliated in only a few areas, and are intrusive into metasedimentary rocks believed to be late Paleozoic in age.

An older group of scattered intrusive bodies is cut by the Jurassic (?) intrusives just described. In general they are more basic and commonly are gabbroic or dioritic. They also are more foliated. These rocks are intrusive into the late Paleozoic (?) strata, but their intrusion may have been in part contemporaneous with the deformation of that terrane. They probably are late Paleozoic or early Mesozoic in age. Some local masses of coarse-grained, commonly highly foliated intrusive rocks apparently are still older, and may be pre-Cambrian.

Tertiary Rocks within the Mountains

So far as is known, no Cretaceous formations of either sedimentary or igneous origin are present within or along the flanks of the Tehachapi Mountains.

Tertiary sedimentary strata, with associated lavas and pyroclastic rocks, occur within the mountains northeast of Tehachapi and north

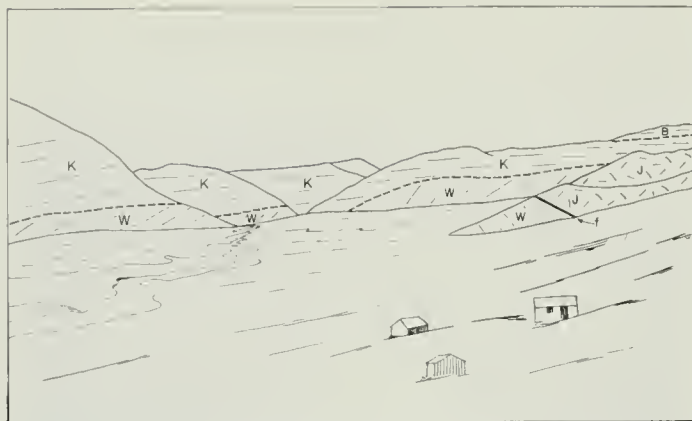


FIGURE 3. View northward up Cache Creek from a point about 1.5 miles east of Monolith. Beds of upper Miocene Bopesta formation (B) rest upon volcanic rocks of upper or middle Miocene Kinnick formation (K), which in turn rest with strong angular unconformity upon continental strata of lower Tertiary Witnet formation (W). Pre-Cretaceous crystalline rocks (J) have been thrust over overturned Witnet strata along a fault (f) of pre-Kinnick age. *Sketched from a photograph.*

of Monolith, where they underlie an area of perhaps 50 square miles. Three nonmarine formations, all at least moderately deformed, constitute this body of younger rocks; in order of decreasing age, these are the Witnet, Kinnick, and Bopesta formations.

Witnet Formation. The oldest of the three Tertiary formations, the Witnet, is the least widely exposed; it underlies an area of only a few square miles along Cache Creek and lower Oil Canyon about 5 miles northeast of Monolith. It consists mainly of beds, each generally a few feet thick, of coarse gray arkose alternating with thinner beds of dark sandy shale or siltstone. The arkose contains both angular fragments of volcanic rocks and locally numerous well-rounded pebbles and small boulders of quartz and quartzite. In general the materials are rather poorly sorted and the bedding is rude. The strata stand at steep angles, and are in part overturned. Their exposed thickness is not less than 4,000 feet, but neither the top nor the base of the formation is exposed.

In spite of repeated search, no fossil material of any kind has been found in the Witnet beds. Miocene strata lie with strong angular unconformity across their upturned edges (fig. 3), as is beautifully shown at the confluence of Oil Canyon and Cache Creek, and in turn they overlie the granitic rocks of the region. They appear to be much less lithified than the Cretaceous formations of the Califor-

nia Coast Ranges. Although they are distant from the nearest exposures of Sespe strata, they resemble some parts of this Oligocene Coast Range formation more closely than any other sedimentary unit. The Witnet formation is therefore of almost certain early Tertiary age, and may be Oligocene. Its arkosic character, the poor sorting of its materials, its rude bedding, the lack of fossils in it, and the angular form of its larger clasts indicate a continental, probably largely terrestrial, mode of deposition under arid or semi-arid climatic conditions. The numerous well-rounded quartz pebbles and cobbles, incongruous among arkosic and angular materials, presumably were derived in already-worn form from some older conglomeratic formation.

Kinnick Formation. In contrast to the underlying Witnet formation and the overlying Bopesta formation, the Kinnick formation consists largely of volcanic debris. It underlies an area of about 25 square miles north of Monolith, between Cache and Whiterock Creeks and along Sand Canyon. The beds that appear rather conspicuously in the hills immediately north of the cement plant at Monolith, and that are utilized to some extent in cement making, mark the southern end of this outcrop area of the Kinnick formation. A small isolated patch of sedimentary strata 1 mile to 3 miles northwest of Tehachapi probably was originally continuous with the upper part of the Kinnick section. Presumably the Kinnick beds extend southward and underlie the alluvium of at least part of Tehachapi Valley.

The formation consists mainly of green and other highly colored basic volcanic tuffs and some coarse agglomerates. Basic lavas constitute only a small part of the section. The upper few hundred feet of the formation consists of gray sandy clays that locally are interbedded with white fresh-water diatomite and gray and yellow cherts. The total thickness of the Kinnick is not less than 1,500 feet.

No fossils have been found in the pyroclastic lower and middle parts of the formation, but the sandy clay beds in the upper part have yielded the Phillips Ranch mammalian fauna. This fauna comprises several forms, including the genus *Merychippus* (Buwalda, 1916), and is presumably of middle or late Miocene age.

The Kinnick formation lies with strong angular unconformity upon the Witnet formation. It appears to be conformable with the overlying Bopesta formation, and is distinguished from it by a marked upward coarsening of the strata.

Some parts of the Kinnick section contain fossil leaves of deciduous trees, and also palm fronds. Much of the formation is well sorted and sharply stratified, and the sedimentary upper part is fine grained and water-laid. Some of these beds closely resemble playa deposits, and fossils representing several species of herbivorous mammals are

found in them. It appears that the formation was deposited in a region of active volcanism and not very great relief, and under climatic conditions that probably were semi-arid rather than arid.

Bopesta Formation. The youngest of the three Tertiary formations, the Bopesta, is widely exposed in spectacular badlands (fig. 4) east of upper Cache Creek and 6 to 7 miles northeast of Monolith. It consists mainly of white to tan-colored, fine- to coarse-grained quartzose sandstone containing some ash and larger fragments of volcanic rock. Some beds are conglomeratic, and some gray sandy shale also is present. The formation extends northward under Cache Peak. It is moderately deformed (fig. 5), with dips up to about 30 degrees, and its thickness is not less than 3,500 feet.

Vertebrate fossil material has been found in some abundance in the lower and middle thirds of the section. Known as the Cache Peak fauna (Buwalda, 1916), it contains several mammalian species and is clearly of late Miocene age. It was previously thought that the Bopesta formation might be unconformable upon the Kinnick formation, because the dominant species of *Merychippus* in the Phillips Ranch fauna of the Kinnick formation is a small and apparently primitive form formerly thought to be of early Miocene age. This would mean that rocks of middle Miocene age are missing between the Kinnick and the Bopesta sections. More recent study of the Phillips Ranch fauna, however, seems to indicate that it is little older than the Cache Peak fauna, a conclusion that is compatible with the apparent structural conformity between the two formations.

Most of the constituent materials in the Bopesta beds are well rounded, and sorting in much of the formation is fairly good. Distinctness of bedding ranges from vague to sharp, the coarser material being in general the least definitely stratified. Cementation is highly variable; most of the strata are rather incoherent, but others are cliff-makers and aid in producing the very bold and picturesque badlands. The nature of the lithology and the vertebrate remains suggest deposition under semi-arid to humid conditions. Some of the materials apparently were lacustrine, whereas others probably were deposited by streams building up alluvial fans. The bouldery character of some of the coarse sandstone beds suggests considerable relief in the area that supplied the debris, and the generally rounded character of the debris and the paucity of arkosic material suggest a humid climate for those surrounding uplands.

Lavas and pyroclastic rocks, mainly of andesitic composition, overlie the Bopesta formation at Cache Peak and in some of the adjacent areas. Still younger are thin flows of olivine basalt 1 mile to 3 miles northeast of Monolith. They lie across the edges of the Kinnick formation, and probably are of Quaternary age.



FIGURE 4. View northeastward at gently tilted continental upper Miocene strata of mammal-bearing Bopesta formation east of upper Cache Creek, south of Cache Peak.

Tehachapi Formation. On the north side of the west end of Tehachapi Valley, 1 mile to 3 miles west of Tehachapi, several hundred feet of a coarse fanglomeratic unit of probable late Pliocene or early Quaternary age, termed by Lawson (1906) the Tehachapi formation, overlies gray tuffaceous shale, sandstone, and chert that probably are the equivalent of the upper part of the Kinnick formation. The Tehachapi beds dip toward the valley at about 10° ; they are probably unconformable on the Kinnick(?) beds, which here dip somewhat more steeply. These fanglomeratic strata indicate that at least part of the development of Tehachapi Valley took place in later Pliocene or early Quaternary time.

Tertiary Geology along San Joaquin Valley Border

The Tehachapi Mountains present a bold northwest front toward the San Joaquin Valley from Grapevine Canyon on the southwest to Caliente Creek and the Southern Pacific Railway tracks on the northeast. This front consists of three segments. The two end segments, each about a third of the total length, trend northeast, and the somewhat shorter middle segment, east of the Tejon Hills, trends northwest. The entire front consists dominantly of pre-Cretaceous crystalline rocks, but Tertiary strata are exposed in strips a few miles in maximum width along the base. These sedimentary formations, commonly several thousands of feet thick, dip away from the mountains at moderate to steep angles, and the upper parts of the sections are concealed in many places beneath overlapping valley alluvium.

In the southwestern part of this bordering apron of stratified rocks, near Grapevine Canyon and the Coast Ranges, the Tertiary formations are mainly marine; northeastward along the mountain front, however, nonmarine beds and volcanic rocks become progressively more abundant. Near Grapevine Canyon the Tertiary section consists of several thousand feet of gray marine sandstone and siltstone (type section of the upper Eocene Tejon formation), above which are some hundreds of feet of Oligocene(?) land-laid beds (Tecuya formation). Resting upon these are several thousand feet of lower Miocene Vaqueros marine beds and a similar thickness of middle Miocene Maricopa marine diatomaceous shale. The Tecuya formation is unconformable on the Tejon, but in general the Tertiary section shows little angular discordance. The beds are steeply tilted and partly overturned at Grapevine Canyon, but farther northeast, toward Tejon Ranch, the northwesterly dips gradually decrease to moderate angles (Hoots, 1930).

In the Tejon Hills, about 15 miles northeast of the mouth of Grapevine Canyon, several hundred feet of middle Miocene marine strata rests unconformably on the pre-Cretaceous rocks at the base of the scarp. The strata dip moderately toward the valley, and thicken rapidly in that direction. Resting unconformably upon them are some hundreds of feet of upper Miocene marine Santa Margarita beds, which in turn are overlain without visible unconformity by Pliocene nonmarine strata of the Chanac formation, all dipping gently away from the mountains (fig. 6).

For about 8 miles north of the Tejon Hills no Tertiary formations crop out along the west base of the Tehachapi Mountains, but at Caliente Creek a strip of Tertiary strata several miles wide extends back into the range for a distance of nearly 10 miles to points beyond the town of Caliente (Dibblee, 1953). These strata, about 3,000 feet in thickness, have been dropped into the crystalline basement terrane by movement on the Edison fault, which bounds them on the south. The section consists of the Oligocene (?) Walker formation, the lower Miocene Ilmon basalt, the lower Miocene Freeman-Jewett shale, the Miocene Bena gravels, and the Pliocene Kern River gravels. Only the Freeman-Jewett shale, about 500 feet thick, is of marine origin. The bulk of the section is coarse grained, and some of it is dominantly volcanic in origin. The Pliocene Kern River gravels lie unconformably on the older Tertiary formations, and the Miocene strata have moderate to steep dips. Clearly this foothill belt experienced vigorous deformation in both Tertiary and post-Tertiary time.

Tertiary Geology on Mojave Desert Margin

Tertiary formations are exposed along a part of the southeast base of the Tehachapi Mountains. They are in part marine in the



FIGURE 5. View northward toward upper Miocene continental strata of Bopsta formation south of Cache Peak, showing folding along northeast-trending axes.

southwestern portion of the outcrop area, and wholly nonmarine farther northeast. In places they dip off the older rocks of the range and under the alluvium of the Mojave Desert, and in places they have been faulted down against the basement rocks.

Near Quail Lake, in the southwestern portion of the Mojave Desert front of the range Crowell (1952) and Wiese (1950) have mapped several thousands of feet of upper Miocene Santa Margarita formation, consisting of marine sandstone, conglomerate, and shale, and extending for about 4 miles northeastward from the San Andreas fault. Miocene continental deposits, presumably 5,000 to 8,000 feet thick, overlie the Santa Margarita and extend about 10 miles northeastward from the fault. These beds may be in part little different in age from the Santa Margarita section. Pliocene fresh-water lake beds, mainly siltstone, clay, and marl, also crop out along the southeast foothills of the range for about 8 miles. They may be in part equivalent to the upper part of the Miocene continental deposits, and have a maximum thickness of approximately 5,000 feet. Pleistocene terrace deposits and alluvium as much as several hundred feet thick lie unconformably upon all the older formations. Dipping from a few degrees to as much as 25 degrees, they record Quaternary tilting and faulting along the southeast flank of the range.

No Tertiary formations are known along the desert margin of the Tehachapi Mountains for a distance of about 20 miles northeast of the Tertiary exposures just mentioned, but a few miles northwest of the town of Mojave a strip of land-laid sediments appears along the south side of the east-west ridge that lies south of the railroad



FIGURE 6. Typical badland exposure of continental lower Pliocene Chanac formation in Tejon Hills. The beds dip gently toward the San Joaquin Valley.

and lower Cache Creek. These strata often have been referred to as the Warren beds or Warren formation. They have been dropped down against a ridge of crystalline rocks along an apparently normal fault; the Garlock fault lies north of the ridge. The beds consist mainly of arkosic sandstone with one or more thin layers of volcanic ash. The total thickness exposed is several hundred feet. Vertebrate fossil remains indicate that the strata are approximately early Pliocene in age, and hence the equivalent of the Ricardo beds. They are gently to moderately folded.

No Tertiary strata occur along the southeast base of the range for 20 miles beyond the patch of Warren beds northwest of Mojave. At Jawbone and Redrock Canyons, still farther northeast, are extensive exposures of the Ricardo formation, consisting of about 7,000 feet of lower Pliocene terrestrial sandstone, conglomerate, and siltstone, with volcanic rocks. This section has been faulted down along the base of the eastern part of the Tehachapi Mountains and along the El Paso Mountains, and has been tilted northwestward at angles of about 30° by the uplift of the latter range (Dibblee, 1952).

STRUCTURE

Pre-Cretaceous Structural Features

The structure in the patches of pre-Cretaceous stratified rocks that are scattered through the Tehachapi Mountains is diverse, but is not yet well known. Elongate strips of Paleozoic (?) limestone and quartzite north of Tehachapi Valley commonly trend north to northwest, and the strata stand at steep angles; many exceptions are

known, however, especially in the smaller patches. In the El Paso Mountains immediately to the east, Dibblee (1952) has described Permian strata with an apparent thickness of 23,000 feet that likewise trend north to northwest. Farther north, in the Kern River area, are inliers of old sediments with similar trend.

These formations, which have been intruded by the Mesozoic granitic rocks, probably were folded during Nevadan or Jurassic time, along with the pre-Cretaceous sedimentary formations of the Sierra Nevada farther north. Thus the area of the Tehachapi Mountains may well have been a part of the original Sierra Nevada. On the other hand, along the Garlock fault north of Mojave and at certain other localities, elongate strips of old rocks trend east to northeast, or roughly parallel to the Garlock fault. These features suggest that the east-west structural trend exhibited in the Transverse Range province to the south and southwest may have been initiated long before Tertiary time.

Tertiary Structural Features

The present Tehachapi Mountains are a product of Cenozoic deformation. The range is bounded on both sides by complex fault zones and by strips of sharply upturned Cenozoic formations. It is not merely an anticlinal arch, but is a complex horst, with both faulting and warping at its margins.

Structure along San Joaquin Valley Margin. As already noted, the northwest margin of the Tehachapi Mountains comprises two end segments that trend about N. 50° E., or roughly parallel to the Garlock fault on the opposite side of the range, and a third or intermediate segment that trends at right angles to the other two. These three divisions of the San Joaquin Valley front are determined by separate structural features of somewhat different type.

The northeast segment, extending for about 15 miles northeastward from the Tejon Hills to points beyond Caliente Creek and the Southern Pacific Railroad, is determined by the active White Wolf fault. It was on this break that the Arvin-Tehachapi earthquake of July 21, 1952, occurred; this was one of the strongest shocks in southern California since 1857, and the strongest in the entire State since the San Francisco earthquake of 1906. The fault lies along the base of the spectacular northwest-facing Bear Mountain scarp, which is about 5,000 feet in height. Extensive geological, seismological, and geodetic studies in connection with the 1952 earthquake indicate that the fault is of reverse character, dipping southeastward under the mountains at a probable angle near the surface of $45^\circ \pm 15^\circ$. Northeast of the Tejon Hills the fault is bounded on both sides by pre-Cretaceous crystalline rocks, except at Caliente Creek, where small masses of Bealville conglomerate, considered by Dibblee (1953)

to be of Oligocene age, have been dropped down against the older rocks along the fault. At the Tejon Hills the folds in the Tertiary formations, the youngest of which is the Pliocene Chanae, are apparently cut off by the fault, which continues southwestward beneath the Quaternary alluvium of the San Joaquin Valley for about 15 miles to Wheeler Ridge or beyond.

The epicenter of the 1952 earthquake was on the south side of Wheeler Ridge. Northeastward from this ridge, geophysical exploration by the Richfield Oil Corporation demonstrates that the total offset of the basement surface along the White Wolf fault is about 10,000 feet. Geodetic work by the U. S. Coast and Geodetic Survey indicates that northeast of the Tejon Hills the upper side of the fault moved northward 2 to 3 feet horizontally and rose about 2 feet, while the northwest side sank about the same amount in connection with the recent earthquake, but the points of both maximum uplift and subsidence were several miles from the fault, with apparently no sharp vertical offset at the fault. The recent fault movement was therefore presumably oblique slip, but mainly dip slip. West of the Tejon Hills the horizontal displacements of triangulation points were comparable in magnitude but entirely different in direction, being mainly westward on both sides of the fault; unfortunately, only one point was located on the lower block. The vertical change here was also about 2 feet on each side, with the maximum subsidence again occurring several miles northwest, and the maximum uplift several miles southeast, of the fault.

The White Wolf fault developed no fresh traces of displacement on the San Joaquin Valley alluvium during the recent earthquake. Northeast of the Tejon Hills tremendous landsliding on the Bear Mountain scarp during past centuries has produced a topography and a macerated rock mass across the approximate trace of the fault such that only numerous disconnected soil ruptures of very diverse trends and amounts and directions of offset were formed. However, several huge new cuts, developed during revisions of four Southern Pacific Railroad tunnels that were damaged by the earthquake, revealed at least three fractures in the bedrock. Taken to be branches of the fault, these breaks dip 30° to 45° southeastward and under Bear Mountain.

The middle segment of the San Joaquin Valley front of the Tehachapi Mountains trends northwest. The great scarp rising from the White Wolf fault turns a right angle at the Tejon Hills, and continues southeastward, with a height of about 2,000 feet, along the northeast side of Tejon Creek canyon practically to the summit of the range. The presumed fault responsible for this scarp was termed the Tejon Canyon fault by Hoots (1930). There is little structural evidence for this fault except near its northwest end, where at one

locality Santa Margarita beds butt against older granitic rocks. The Tertiary formations of the Tejon Hills in general lie with depositional contact on these granitic rocks, but dip away from the mountains at angles of 10° to 50° . The boldness of the scarp, and the sharp topographic boundaries between it and the Cummings Valley upland above and the Tejon Valley below, indicate either a northwest-trending fault or a very sharp warp, or a combination of the two, developed in post-Chanae time.

The third or southwest segment, closing in the extreme southeast end of the San Joaquin Valley, extends from Tejon Creek to Grapevine Canyon. At the mouth of this latter canyon, upper Eocene Tejon strata stand at very steep angles or are overturned toward the valley. Hoots (1930) showed probable fault relations here, and, considering the prevalence of reverse and overthrust faulting west of Grapevine Canyon, the boldness of the scarp of old rocks that rises above the Tertiary formations, and the overturned structure of the Tertiary beds, it is almost certain that strong reverse or overthrust faulting has occurred here and for some distance to the east.

East of Grapevine Canyon, the Miocene strata, finally lying in depositional contact on the older rocks, dip less and less steeply as they are traced toward the Tejon Ranch headquarters. But as far as Tejon Creek the steep bedrock front, meeting the Tehachapi Mountains upland with a rather definite angle, must indicate either faulting near the base of the scarp (but topographically above the basal contact line of the sediments) or a sharp warp in the bedrock. And it is probably not a coincidence that a rather bold scarp in the older rocks lies nearly in line with it on the opposite side of Tejon Creek, along the southeast side of Cummings Valley, on the block uplifted by movement along the Tejon Canyon fault. The Cummings Valley scarp is more or less continuous with the impressive escarpment along the south side of Tehachapi Valley, and the structural break along its base may be continuous with the Cache Creek reverse fault or overthrust, as will be mentioned farther on.

Structure along Mojave Desert Side of Range. It has often been held that the Tehachapi Mountains were uplifted and differentiated from the Mojave Desert block by movement on the Garlock fault, but this is true only for about the northeastern third of the range from the San Andreas fault to Jawbone Canyon. From a point near Warren, northwest of Mojave, northeastward to Jawbone Canyon, the range front is a straight, bold fault scarp 2,000 to 2,500 feet high, with the Garlock fault at its base. This break is mainly a strike-slip fault, with left-lateral displacement that has been estimated to be at least several miles.

Southwestward from Warren, the Garlock fault lies within the mountains, at average distances from their southeastern base that

increase irregularly from a mile or two near Warren to 6 or 7 miles near the San Andreas fault. For nearly all of the distance from Warren to Oak Creek, the apparently normal Warren fault, subparallel to and probably a branch of the Garlock fault, defines the southeast base of the mountains, the slice between the two faults having been elevated along with the mountain mass. Southwestward from Oak Creek to the point where Tertiary strata appear along the base of the range, the physiography suggests that the front of the range is determined in part by local faults that make large angles with the Garlock fault, and in part by warping. The Garlock fault, which here lies well within the range, gives little indication of dip-slip movement, and seems to have had little or no part in uplifting the Tehachapi Mountains. In the most southwesterly 10 miles of the range front, the Tertiary and older Quaternary sediments dip in general toward the desert region, and a number of faults have been mapped by Crowell (1952) and by Fine (1947). Most of them have trends that differ considerably from that of the Garlock, and are not connected with this major break. The faults presumably had some relation to the uplift of the range, but this section of the range front apparently was determined mainly by warping.

Structure within the Range. In contrast to the rigid Sierra Nevada block, which was little deformed during Tertiary time, the Tehachapi Mountains were both strongly folded and faulted internally, and probably at several times during the Tertiary period. The Witnet formation, early Miocene or pre-Miocene in age, dips very steeply northward along Oil Canyon and gently southward along Cache Creek half a mile north of its junction with Oil Canyon, and hence apparently forms an acute syncline that trends northeast. The overlying middle or upper Miocene Kinnick and Bopesta formations likewise have been folded synclinally but less acutely so, and the broad northeast-trending fold includes several lesser folds (fig. 5) and is cut by numerous minor faults. Basic lavas, probably of Pliocene age, apparently lie unconformably on the Miocene strata. There are evidences of still other Tertiary episodes of deformation, as in the Coast Ranges to the west.

Along the southeast sides of Cache Creek and Oil Canyon, east of Monolith, the pre-Cretaceous crystalline rocks have been thrust northwestward over the pre-middle Miocene Witnet formation, which has been acutely upturned and overturned (fig. 3). This thrust, the Oil Canyon fault, dips 30° to 45° southeast. It apparently is mainly or entirely of pre-middle Miocene age, for Kinnick strata have not been found to be cut by it and patches of Kinnick, but little deformed, rest on the older rocks southeast of the fault. The surface trace of the fault is terminated northeastward by a cross fault that drops Kinnick strata down on the east side, but its alignment sug-

gests that it may well continue in the older rocks and be responsible for Lone Tree Canyon, in which case it continues to, and is cut off by, the Garlock fault. Southwestward the Oil Canyon fault passes beneath the alluvium of Tehachapi Valley. It may terminate against an east-west fault that Lawson (1906) predicated along the south margin of Tehachapi Valley, but it appears equally probable that the Oil Canyon thrust turns somewhat westward, becomes the Tehachapi Valley fault, and is responsible for both Tehachapi and Cummings Valleys. Continuing southwestward, it would be offset by the Tejon Canyon fault, but it may well be a continuation of the zone of sharp deformation that bounds the northwest side of the Tehachapi Mountains from Tejon Canyon to Grapevine Canyon.

A second set of faults within the Tehachapi Mountains trends roughly northwest, and includes the Tejon Canyon fault, previously referred to, and the two faults that bound Bear Mountain on the northeast and southwest sides, and between which the mountain was hoisted to its present height of nearly 7,000 feet. It is not known whether these faults continue northwestward on the floor of the San Joaquin Valley beyond the White Wolf fault, or whether they terminate against it, but it is known that similar northwest-trending faults extend discontinuously northwestward beneath the valley toward structures of similar trend that plunge southeastward beneath the valley alluvium from the eastern margin of the Coast Ranges in the Coalinga area. Similar northwest-trending faults drop Tertiary formations down against the basement rocks along the eastern margin of the San Joaquin Valley east and north of Bakersfield; the great fault-line searp at the mouth of the Kern River Gorge, 12 miles northeast of Bakersfield, is one of these. These faults are taken to be Central Coast Range structures that traverse obliquely the southern San Joaquin Valley floor and reach into the Tehachapi Mountains.

ORIGIN OF THE TEHACHAPI MOUNTAINS

The Tehachapi Mountains bear little structural or genetic relation to the Sierra Nevada, with which they merge on the northeast. They do not trend north, they do not constitute a tilted block, and the great north-trending fault zone that bounds the Sierra Nevada on the east does not reach into the Tehachapi country and has no relation to the Garlock fault, which lies along or within the south margin of the Tehachapi Mountains. On the other hand, the range trends more nearly parallel to the Transverse Ranges to the south and southwest, and it lies east of and on the projection of the structural lines of the Transverse Ranges. Instead of being a tilted block, it is a plateau or complex horst elevated between faults or sharp flexures along its San Joaquin Valley and Mojave Desert margins. It has internal structures that in nature and trend seem to be extensions

of both the east-trending structures of the Transverse Ranges to the west and of the northwest-trending structures of the Central Coast Ranges projected obliquely southeastward across the San Joaquin Valley. Like the Coast Ranges, the Tehachapi Mountains experienced several mountain-making disturbances during the Tertiary period.

It is not known whether the Tehachapi Mountains ever were largely covered by Tertiary sedimentary formations similar to those in the Coast Ranges, and it is clear that some interior parts, such as that north of Monolith, were not. These parts are still underlain by some Tertiary deposits that are different from deposits of similar ages in the Coast Ranges. Typical Coast-Range Tertiary formations thousands of feet thick now dip off the margins of the Tehachapi Mountains, and plainly extended for considerable distances into the interior of the present range. In general the range apparently stood higher than the Coast Range country west of it during at least a large part of the Tertiary period, so that it was covered only in part by marine sediments and received land-laid deposits in other parts. It apparently rose much higher in late Cenozoic time, so that it is now mainly old crystalline rocks at the surface, whereas the Coast Ranges west of it still carry great thicknesses of Tertiary formations.

ORIGIN OF THE TEHACHAPI VALLEY SYSTEM

One of the remarkable features of the upland surface of the complex horst that makes the Tehachapi Mountains is the existence on it of several broad, flat-floored valleys. Lawson (1904) described the general geologic nature of these striking depressions picturesquely and accurately nearly 50 years ago. They lie at an altitude of about 4,000 feet, and hence are high above both the Mojave Desert and the San Joaquin Valley. Streams are now heading back into them from the San Joaquin Valley side, and will eventually destroy them.

The largest of these upland depressions is Tehachapi Valley, about 10 miles long and 3 miles wide, which trends east athwart the range and affords the pass for the railroad line and one of the main highways between southern and central California. To the west of it lie Brite Valley, Cummings Valley, and Bear Valley, which are smaller but otherwise similar depressions. All these valleys contain Quaternary alluvium as much as several hundred feet deep. Each of the valleys is bounded on one or more sides by a bold scarp that rises abruptly from its alluvial floor and that has been developed on old crystalline rocks. Apparently in large part because of these striking scarps, Lawson (1904) concluded that the Tehachapi valleys were formed chiefly by Quaternary faulting. The gentle southerly tilt of the upper Pliocene or Quaternary Tehachapi formation tends to support this view, although the tilt may be related to a synclinal downwarping of that formation and the underlying Cable, Tank, and

Atlas formations as a separate episode, as Lawson suggested. Moreover, it is clear that Tehachapi Valley was in part eroded out of the Tehachapi formation and the Kinnick formation, as the considerable thickness of the latter unit exposed at and north of Monolith originally must have extended southward into the area now occupied by the valley and must have been removed by erosion before the thick body of alluvium was deposited on the valley floor.

The writer knows of no Tertiary strata on the south side of Tehachapi Valley or in Brite, Cummings, or Bear Valleys, and hence has no clue as to their original distribution in these valleys. The apparently necessary inference that Tehachapi Valley was at least in part formed by erosional removal of these less resistant beds, and the physiographic similarity of these other three valleys to the larger valley, leads to the supposition that they also are at least in part excavational rather than entirely tectonic in origin. No evidence of faulting so recent as to cut the alluvium has been found along any of the scarps. The northwest-trending scarps on the two sides of Bear Mountain appear to be bolder and younger than the east-trending scarps along the south side of Tehachapi, Brite, and Cummings Valleys, and it is entirely possible that the former are true fault scarps and that the latter are in part fault-line scarps resulting from the erosional excavation of Tertiary beds to form the three valleys. The excavation presumably would have occurred during or after uplift of the horst.

GEOLOGIC HISTORY OF THE TEHACHAPI MOUNTAINS

The geologic history of the Tehachapi Mountains is at best a very incomplete record of the episodes of uplift, erosion, deposition of sediments, volcanism, folding, faulting, and metamorphism, and is further limited by the small fraction of the range that has been mapped or studied in detail. Probably the earliest known event in the evolution of the range is recorded in patches of metamorphosed sediments believed to be of pre-Cambrian age. These now are mainly schist (the Pelona schist), and are present between Tehachapi and Mojave, as well as in larger areas in the southwest part of the range, where they have been described by Wiese (1950). These rocks are believed to represent mainly the fine-grained sediments laid down in one or more invasions of a pre-Cambrian sea.

Another epoch of pre-Cambrian marine deposition probably is represented by a body of rocks, termed by Wiese (1950) the "gneiss complex," in the southwestern part of the range. Partly old sediments and partly intrusive rocks, this complex indicates another long chapter of pre-Cambrian history, but whether this was earlier or later than the deposition of the Pelona schist is not certain.

What occurred in this region during the early and middle parts of the Paleozoic era is not known, but probably in Carboniferous

time another marine transgression resulted in deposition of a thick section of limestones, sandstones, and other sedimentary strata. Diastrophism followed in later Paleozoic or early Mesozoic time, and during or after the deformation intrusive rocks invaded the sediments. These igneous bodies were more basic in composition than the widespread granodioritic intrusives of later Mesozoic age, and commonly are now more gneissic.

There is no known record of Mesozoic sedimentation in the entire Tehachapi Mountains, but presumably during the Jurassic period widespread intrusion of batholithic rocks occurred, ranging in composition from gabbro to granite but dominantly of granodioritic type. The exact date of this igneous activity has not been determined in this region, but the similarity of the rock types to those in the Sierra Nevada farther north has led to the assumption that these intrusive formations are "part of the granites of the Sierra Nevada."

Presumably just preceding and during the intrusion of the granodioritic rocks in Jurassic time, vigorous mountain making affected this region as it did the northern Sierra Nevada and large parts of western Nevada and southeastern California. Although the history of the Tehachapi Mountains in post-Mesozoic time seems to have been rather independent of that of the Sierra Nevada, the tectonic affinity of these regions in Jurassic time seems to be strongly indicated by the similarity in trends of the remaining patches of Paleozoic sedimentary strata, and by the structural trends in the magnificent section of Permian strata so excellently mapped in great detail by Dibblee (1952) in the El Paso Range, the mountain mass that is adjacent to the Tehachapi Mountains on the east. Deep and presumably long-continued erosion, embracing later Jurassic, Cretaceous, and perhaps early Tertiary time, stripped away the roof rocks of these Jurassic intrusive bodies in the Tehachapi Mountains and much of the surrounding region, except for scattered patches of Paleozoic and pre-Cambrian sediments and gneissic intrusives.

What episodes of mountain making, deposition, and erosion occurred on the granitic platform of what is now the Tehachapi Mountains during Cretaceous and early Tertiary time is not known. At some date previous to middle Miocene time, and presumably during the Oligocene epoch, deformation within the range was sufficiently intense to result in deposition of angular arkosic sediments and interstratified dark shales nearly a mile thick. Well-rounded and polished cobbles among these angular, presumably land-laid sediments (Witnet formation) imply the erosional destruction of some older coarse-grained sedimentary formation in the region, as well as earlier mountain making leading to the deposition of that unknown sedimentary unit.

Presumably in later Oligocene or in early Miocene time vigorous deformation again occurred. The Witnet formation was strongly folded, and granitic rocks were thrust over it from the south along the Oil Canyon fault. Then, as far as can be determined from the limited remaining areas, erosion again reduced much of the relief that resulted from the mountain making.

In middle and upper Miocene time volcanism led to accumulation of many hundreds of feet of basic lavas and associated highly colored tuffs (Kinnick formation). This activity must have been accompanied by further crustal deformation, for resting on the volcanic rocks are some thousands of feet of land-laid, largely non-volcanic sediments (Bopesta formation) clearly derived from highlands surrounding the basin of deposition. They resulted from weathering, transportation, and deposition under semi-arid conditions. Both the Kinnick and Bopesta beds contain vertebrate fossils that demonstrate their middle or late Miocene age.

On the San Joaquin Valley side of the Tehachapi Mountains is recorded a Tertiary history of repeated uplift and depression of the mountain mass relative to sealevel or to baselevel. Near Grapevine Canyon the sea must have covered neighboring parts of the range during upper Eocene time, when the Tejon formation was deposited to a thickness of thousands of feet at its type section. Emergence was followed by the deposition of the Oligocene (?) Tecuya formation, and at about this same time the thick section of the land-laid Walker formation, with its Bealville conglomerate, was deposited farther northeast, in the Caliente Creek region (Dibblee, 1953). It is not known whether these formations were laid down earlier than, contemporaneously with, or later than the Witnet formation within the range.

Little is known about the Eocene and Oligocene history of the southeast margin of the range, as no rocks of these ages have been recognized there. However, the type section of the Rosamond formation, mainly volcanic rocks and continental beds of probable Miocene age, accumulated in the neighboring part of what is now the Mojave Desert. In upper Miocene time the sea invaded the western end of the Mojave Desert and deposited Santa Margarita beds on the southeast flanks of the western part of the Tehachapi Mountains, and this was followed by accumulation of a considerable thickness of continental beds. This is the only known record of post-Paleozoic marine deposition in the Tehachapi Mountains or adjacent parts of the Mojave Desert.

In Pliocene time a fresh-water lake received some thousands of feet of sediments along the Antelope Valley margin of the range, presumably as the result of uplift of the range and relative depression of the adjoining margin of the Mojave Desert. Farther north-

east, in an area northwest of Mojave and between that area and Redrock Canyon still farther northeast, terrestrial strata (Ricardo formation) accumulated to similar thicknesses, and entombed vertebrate fossils that provide a good view of the nature of mammalian life roaming the semi-arid plains and hill country of that time.

The deposition of the continental Ricardo formation on the southeast margin of the range, and of the Chanac formation and the Kern River gravels along the northwest base of the range, doubtless resulted from further uplift and deformation within the Tehachapi Mountains in post-Miocene time. No Pliocene strata were laid down within the range, so far as is known, but the Bopesta formation was moderately folded along east-west axes, and was cut by faults. Probably, but not certainly, both it and the older formations on which it rests were bevelled off, and in later Pliocene time andesitic flows and agglomerates, of which only patches now remain, probably buried a large part of these Tertiary sediments. One remnant of the flows now caps Cache Peak, north of Tehachapi Valley, at an altitude of 6,700 feet.

In late Pliocene and Quaternary time deformation apparently continued within the range, as the Pliocene or Quaternary Tehachapi formation of the northwest corner of Tehachapi Valley was folded and tilted so that it now extends beneath the valley alluvium. If the Tehachapi valley system developed mainly by late faulting, it must have been at this time, as the marginal scarps are in part still bold. Certainly faulting within the range occurred during Quaternary time, as shown by the northeast and southwest faces of Bear Mountain. If the origin of the Tehachapi valleys was mainly erosional, they must have been excavated during Quaternary time. But the larger-scale deformation during Quaternary time was by faulting and warping along both margins of the range, and by elevation of the complex Tehachapi Mountains horst between the two fault systems. The mountain mass rose 2,000 to 3,000 feet with reference to the Mojave Desert block southeast of it, which itself may well have been elevated somewhat at this time, and the mass was lifted 5,000 feet or more with reference to the San Joaquin Valley. To judge by the seismic activity, the locally offset alluvial surfaces, and the freshness of the scarps, this marginal faulting, and presumably the marginal warping and the uplift, are still continuing. In addition, the last episode in the recent history includes the vigorous dissection and degradation initiated by the last uplift of the range.

In summary, the Tertiary history of the Tehachapi Mountains, like that of the Transverse Ranges west and southwest of them, is one of repeated deformation, subsidence, and uplift, with resultant deposition of marine or land-laid sediments and volcanic rocks in

constantly shifting areas and their equally irregular erosional removal, giving rise to numerous unconformities and complex areal distribution and structural relationships. It appears that the range was in existence during most of Tertiary time, as suggested by the structural relations of the sediments along its flanks, but in general it probably stood much lower than at present. The thick Tertiary sediments, now truncated along its margins, must have covered much larger parts of the range during a considerable part of the time, and the continental sediments within the range clearly extended at times over much larger areas. Late in the Cenozoic era—so late that dissection has not yet reached into the interior of its wider parts—the range was uplifted vigorously. This resulted in rapid stripping of sediments both in the interior and along the margins, and produced a complex horst in which old pre-Cretaceous intrusive rocks are widely displayed at the surface.

REFERENCES

- Buwalda, J. P., 1915, Structure of the southern Sierra Nevada, California (abstract): *Geol. Soc. America Bull.*, vol. 26, p. 403.
- Buwalda, J. P., 1916a, New mammalian faunas from Miocene sediments near Tehachapi Pass in the southern Sierra Nevada: *Univ. California, Dept. Geol. Bull.*, vol. 10, pp. 75-85.
- Buwalda, J. P., 1916b, Note on the geology of the Tejon Hills: *Univ. California, Dept. Geol. Bull.*, vol. 10, pp. 113-114.
- Buwalda, J. P., 1920, Fault system at the southern end of the Sierra Nevada, California (abstract): *Geol. Soc. America Bull.*, vol. 31, p. 127.
- Buwalda, J. P., 1935, Tertiary tectonic activity in the Tehachapi region, California (abstract): *Geol. Soc. America Proc.*, 1934, p. 312.
- Crowell, J. C., 1952, Geology of the Lebec quadrangle, California: *California Div. Mines Special Rept.* 24.
- Dibblee, T. W., Jr., 1952, Geology of the Saltdale quadrangle, California: *California Div. Mines Bull.* 160.
- Dibblee, T. W., Jr., 1953, Geology of the Breckenridge Mountain quadrangle, California: *California Div. Mines Bull.* 168.
- Fine, S. E., 1947, Geology of part of the western end of Antelope Valley, California: Master's Thesis, University of California, Los Angeles.
- Goodyear, W. A., 1888, Kern County: *California Min. Bur. Rept.* 8, p. 310.
- Hoots, H. W., 1930, Geology and oil resources along the southern border of San Joaquin Valley, California: *U. S. Geol. Survey Bull.* 812-D.
- Lawson, A. C., 1904, The geomorphology of the Tehachapi Valley system: *Univ. California, Dept. Geol. Bull.*, vol. 4, pp. 431-462.
- Miller, W. J., 1931, Geologic sections across the southern Sierra Nevada of California: *Univ. California, Dept. Geol. Sci., Bull.*, vol. 20, pp. 331-360.
- Miller, W. J., 1946, Crystalline rocks of southern California: *Geol. Soc. America Bull.*, vol. 57, pp. 457-540.
- Miller, W. J., and Webb, R. W., 1940, Descriptive geology of the Kernville quadrangle, California: *California Jour. Mines and Geology*, vol. 36, pp. 343-378.
- Simpson, E. C., 1934, Geology and mineral deposits of the Elizabeth Lake quadrangle, California: *California Jour. Mines and Geology*, vol. 30, pp. 371-416.
- Wiese, J. H., 1950, Geology and mineral resources of the Neenach quadrangle, California: *California Div. Mines Bull.* 153.

10. GEOLOGY OF THE CENTRAL AND SOUTHERN DEATH VALLEY REGION, CALIFORNIA†

BY LEVI F. NOBLE • AND LAUREN A. WRIGHT ••

INTRODUCTION

That the geology of the desert region bordering and including the central and southern parts of Death Valley is exceedingly complex and reflects an unusual geologic history is immediately evident from a glance at the accompanying geologic map (plate 7). Only parts of the region have been studied in detail, so that the geology is imperfectly known; but enough information is available to piece together the broad outline of the salient geologic features set forth below.

The region considered here (plate 7) is 90 miles long in a northerly direction and 57 miles wide. It is characterized by mountain ranges and valleys that for the most part trend north to northwest. The most prominent of these features are the central part of Death Valley and the mountain ranges that bound it—the Panamint Range on the west and the Funeral and Black Mountains on the east. In easterly succession from the Black Mountains lie the Furnace Creek-Greenwater Valley, the Greenwater Range, Amargosa Valley, the Resting Spring Range, Chicago Valley, and the Nopah Range. Southeast of the southern end of the Panamint Range, and separated from it by Wingate Wash, are the Owlshead Mountains which are roughly circular in plan. The east- to southeast-trending Avawatz Mountains lie at the southern end of Death Valley and are separated from the Owlshead Mountains and their westerly extension, the Quail Mountains, by Owl Spring Wash and the Leach trough. The southern part of Death Valley lies between the Owlshead and Black Mountains and is aligned more northwestward than the central part, which trends nearly north. All the topographic features noted above are rather well-defined structural elements, and will be described as such in the discussion to follow.

Published geologic maps (fig. 1) within the area of the accompanying map (plate 7) cover parts of the eastern slope of the Panamint Range (Murphy, 1932; Hopper, 1947); the central Black Mountains (Curry, Contribution 7, Chapter IV); the Virgin Spring area of the southern Black Mountains (Noble, 1941); the Leach Trough-Quail Mountains area south of the Owlshead Mountains (Muehlberger, Map Sheet No. 16, this volume); an area of saline-bearing Tertiary rocks at the north base of the Avawatz Mountains (Johnson and Lewis, in Ver Planck, 1952; Durrell, 1953); the Tecopa area (Mason, 1948); a part of the Saratoga Hills (Wright, 1952a); the Silurian Hills (Kupfer, Map Sheet No. 19, this volume);

and the Alexander Hills area (Wright, Map Sheet No. 17, this volume). Unpublished maps of the Greenwater Range and of the valley of Furnace Creek from Ryan to Death Valley, together with data on the geology of these areas, have been kindly supplied by T. P. Thayer. The writers have utilized all of these sources of information, as well as an unpublished map of the central Black Mountains by H. D. Curry, and Wright's unpublished geologic map of the southern half of the Tecopa quadrangle. All of the area of the accompanying map (plate 7) has been studied in reconnaissance by the writers, but Wright's work has been confined largely to the southeastern and west-central parts.

ROCK FORMATIONS ††

Undifferentiated Earlier Pre-Cambrian Rocks. A complex composed mostly of gray granitic to dioritic gneiss, but containing subordinate quartzite, mica schist, migmatite, amphibolite, carbonate strata, and intrusive bodies of granitic rocks, is extensively exposed in the Black Mountains (fig. 3) and Ibex Hills, and also underlies smaller areas in the southeastern part of the Panamint Range, Greenwater Range, southern Nopah Range, and Alexander Hills. The earlier pre-Cambrian age of this complex is established by the existence of an unconformably overlying section of later pre-Cambrian sedimentary rocks—the Pahrump series. Metamorphic and plutonic igneous rocks, extensively exposed on the north and east slopes of the Avawatz Mountains, on the crest and south slopes of the Owlshead Mountains near Owl Hole Springs, and in the northwestern part of the Funeral Mountains, are probably also earlier pre-Cambrian in age. In the Avawatz Mountains they consist mostly of quartz diorite and quartz diorite gneiss that contains xenoliths of marble; in the Owlshead Mountains they include marble, quartzite, and quartz diorite; and in the Funeral Mountains they include phyllite, schist, marble, quartzite, and quartz diorite gneiss.

Later Pre-Cambrian Rocks. Unmetamorphosed sedimentary rocks and diabase that comprise the later pre-Cambrian Pahrump series crop out at many places in a belt extending from Galena Canyon in the southeastern part of the Panamint Range southeastward for 75 miles to and beyond the Kingston Range at the east margin of the map area (plate 7). Recent studies suggest that metamorphic rocks probably correlative with the Pahrump series form most of the crest and west slopes of the Panamint Range beyond the west border

† Publication authorized by the Director, U. S. Geological Survey.

• Geologist, U. S. Geological Survey.

•• Senior Mining Geologist, California Division of Mines.

†† Not all formation names used in this paper have been recognized by the Geological Survey.

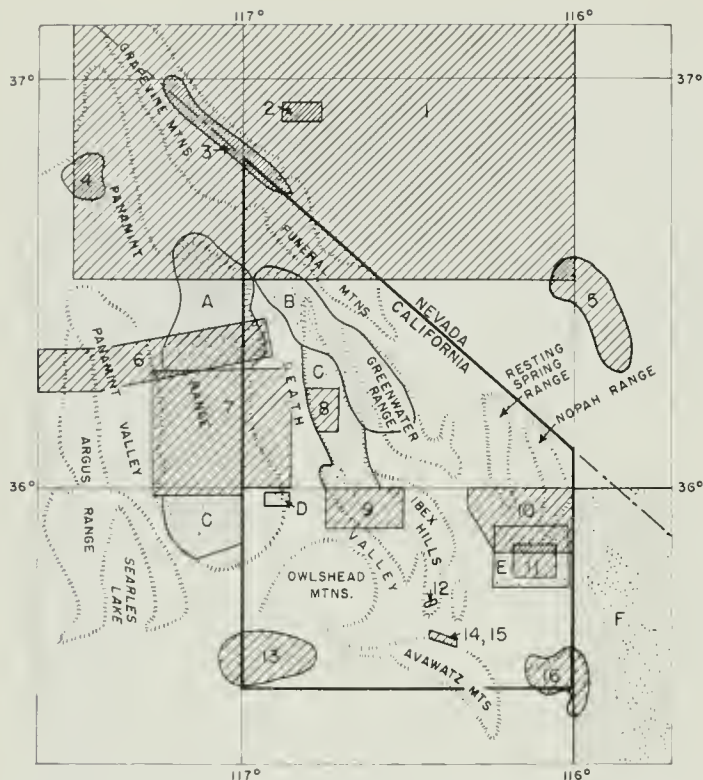


FIGURE 1. Index map of the Death Valley region showing area of plate 7 enclosed in heavy line and areas covered by other maps, published (shaded) and unpublished (dotted). As numbered, the published maps are by the following workers: 1. Ball (1907), 2. Ransome, Emmons, and Garrey (1910), 3. Stock and Bode (1935), 4. McAllister (1952), 5. Nolan (1929), 6. Hopper (1947), 7. Murphy (1932), 8. Curry (1954), 9. Noble (1941), 10. Mason (1948), 11. Wright (1954), 12. Wright (1952a), 13. Muehlberger (1954), 14. Johnson and Lewis in Ver Planck (1952), 15. Durrell (1953), and 16. Kupfer (1954). As lettered, the unpublished maps are by the following workers (A) D. H. Sears, (B) T. P. Thayer, (C) H. D. Curry, (D) L. A. Wright, (E) L. A. Wright, and (F) D. F. Hewett.

of the map area (B. K. Johnson, personal communication, 1954; D. H. Sears, personal communication, 1954).

Throughout the 75-mile belt of unmetamorphosed Pahrump strata, the series is divisible into three formations described by Hewett (1940) in the Kingston Range east of the border of the map (plate 7). The lowest and most extensively exposed is the Crystal Spring formation, which is commonly about 4,000 feet thick and consists mostly of various clastic sedimentary rocks and diabase (Wright, 1949; 1952a). A carbonate member, several hundred feet thick, generally occurs near the middle of the formation and locally has been altered to deposits of commercial talc. This formation is successively overlain by the Beck Spring dolomite, about 1,000 feet thick, and the Kingston Peak formation, which consists mainly of quartzite and conglomeratic quartzite and which probably is several thousand feet in maximum thickness. The Kingston Peak formation contains abundant detritus from both of the lower Pahrump formations, but the unconformity thus indicated has not been detected by mapping.

Cambrian Rocks. In the southern and central Death Valley region, the strata that have been assigned a Cambrian age total about 17,000 feet in thickness and comprise more than three-quarters of the exposures of Paleozoic rocks. The Cambrian section of the Nopah and Resting Spring Ranges has been measured and mapped in greatest detail (Hazzard, 1937; Mason, 1948; Wright, Map Sheet No. 17, this volume). It comprises, from bottom to top, about 1,000 feet of massive Lower Cambrian dolomite (Noonday dolomite), an additional 8,000 feet of Lower Cambrian strata that consist mostly of quartzite and shale (Johnnie formation, Stirling quartzite, and Wood Canyon formation), 5,300 feet of Middle Cambrian dolomite (Cadiz, Bonanza King, and Cornfield Springs formations), and 1,700 feet of Upper Cambrian dolomite (Nopah formation).

The lowest beds that contain diagnostic fossils are high in the Wood Canyon formation, and the fossils are Lower Cambrian. The underlying units, including the Noonday dolomite, apparently are conformable with the Wood Canyon, but no fossils other than algal(?) remains have been recognized in them. Because the Noonday dolomite is separated from the Pahrump series by a widespread angular unconformity, Hazzard (1937) placed the base of the Cambrian at this contact. A marked lithologic change, however, occurs at the base of the Stirling quartzite. The underlying Johnnie formation and Noonday dolomite are lithologically more similar to the rocks of the Pahrump series than to rocks in the overlying Paleozoic formations, show vertical variations in lithology and color that are much more abrupt than variations in the Stirling quartzite and higher formations, and contain algal(?) beds of a type different from those in the higher formations.



FIGURE 2. View westward at east face of Panamint Range, showing Hanaupah Canyon and Telescope Peak (left skyline). The mountain slopes are underlain by Cambrian strata that dip toward viewer. Note size and dissection of Hanaupah fan. Gully dissection of upper part of fan has a relief of about 200 feet. Compare with alluvial fans along Black Mountains on opposite side of valley (fig. 3). *Spence Air Photos.*



FIGURE 3. View eastward at west face of Black Mountains, showing Dantes View on center skyline and Badwater at left of alluvial fan in center of photo. Mountain front consists essentially of earlier pre-Cambrian metamorphic rocks capped by Tertiary volcanic rocks. Relatively dark spur at extreme left of view is surface of north-plunging Badwater turtleback. Floor of Death Valley is rock salt. Note small size and lack of dissection of alluvial fans compared with Hanaupah Canyon fan (fig. 2) on opposite side of valley. *Spence Air Photos.*

The Cambrian rocks of the Panamint Range (Murphy, 1932; Hopper, 1947) and Funeral Mountains, although less well known, appear comparable in thickness with those of the Resting Spring and Nopah Ranges, and consist of essentially the same formations. Most of the rocks designated by Murphy (1932) as the Telescope group are now correlated with the Noonday dolomite and Johnnie formation (D. H. Sears, personal communication, 1954).

Post-Cambrian Paleozoic Rocks. Paleozoic sedimentary rocks of post-Cambrian age occur in relatively intact sections on the northeast flank of the Nopah Range, the southern part of the Funeral Range, and the east flank of the Panamint Range north of Death Valley Canyon. In addition, Permian strata form a wedge enclosed by granite in the Warm Springs Canyon area, in the southeastern Panamint Range.

In the Nopah Range the post-Cambrian Paleozoic section is nearly 7,000 feet thick (Hazzard, 1937; 1951), and all formations, except the Middle Ordovician Eureka quartzite, consist mostly of carbonate strata. The Lower and Upper Ordovician and Silurian rocks are mostly dolomite; the Mississippian and Pennsylvanian rocks are predominantly limestone. The post-Cambrian Paleozoic sections in the Panamint Range and Funeral Mountains are similar in lithology to the one in the Nopah Range, but have not been described in detail. The Panamint Range section probably is thicker than the other two, because it contains the additional Permian unit in Warm Springs Canyon that is at least 4,000 feet thick (C. T. Wruke, personal communication, 1954).

Mesozoic Rocks. Although Mesozoic rocks have not been positively identified in the mapped area, the granitic intrusive rocks described below are probably for the most part Mesozoic in age. Volcanic and fossiliferous sedimentary rocks of Triassic age (B. K. Johnson, personal communication, 1954) are present in Butte Valley, which is in the southern Panamint Range just west of Warm Springs Canyon and just outside the area of the accompanying map. It is possible that Mesozoic volcanic rocks underlie other parts of the Death Valley region and have been mapped with the older Tertiary rocks.

Granitic Intrusive Rocks. Granitic intrusive rocks, whose age and variations in composition are not fully known, are widespread in the Death Valley region. Much the largest body of granite underlies the Owlhead Mountains, and smaller bodies are exposed in the Black, Greenwater, Avawatz, Granite, and southern Panamint Ranges. Most of the granite approximates quartz monzonite in composition. In some areas it is uniformly coarse grained, but in others it is porphyritic or shows a wide variation in texture.

Some granite that intrudes the earlier pre-Cambrian metamorphic complex is pre-Cambrian, as it is truncated by basal beds of the Pahrump series. This granite is not shown on the map. Most of the granite that is shown on the map was intruded in Mesozoic time and is genetically related to similar granite abundant in the desert region of eastern California, as well as in the southern California and Sierra Nevada batholiths. A Mesozoic age is suggested for the granite in Warm Springs Canyon, at the southern end of the Panamint Range, as it does not intrude Tertiary volcanic rocks, but does cut all older rocks including those of Triassic age in Butte Valley, just west of the area mapped.

Some of the granite in the Death Valley region may be Tertiary. Thayer (cited by Noble, 1941, p. 954) has noted that, in the Black Mountains and Greenwater Range, porphyritic granitic rock cuts volcanic rocks that appear to be part of the Artist Drive formation. In an area near the Amargosa River, southwest of the Alexander Hills, porphyritic granite contains xenoliths of volcanic rock whose age is unknown but may be Triassic.

Tertiary Rocks. Volcanic and sedimentary rocks of Tertiary age are widespread in the southern and central parts of the Death Valley region. They underlie Death Valley and all the other large topographic depressions, and lie irregularly upon the slopes and crests of the mountain ranges. In general, the sedimentary rocks (clay shales, siltstones, sandstones, and conglomerates) occupy the depressions, which appear to have existed in Tertiary time as troughs and basins of deposition. At many places the volcanic and sedimentary rocks interfinger.

Within the area of plate 7, Tertiary strata have been dated by fossils at only two localities, and the dating is not precise. Leaves found in the Furnace Creek formation in lower Furnace Creek Wash are believed to be early Pliocene in age (Axelrod, 1940). In the Copper Canyon area, on the west slope of the central part of the Black Mountains, beds that are lithologically similar to the Furnace Creek formation contain animal footprints that indicate an age somewhere between late Miocene and middle Pliocene (Curry, 1941).

In the bordering areas the evidence for dating Tertiary formations likewise is scanty. The oldest Tertiary strata yet recognized in the general region occur on the north side of the Grapevine Range near the head of Titus Canyon, north of the area of plate 7. These have yielded Oligocene Titanotherium remains (Stock and Bode, 1935, pp. 573-579), and are part of the Titus Canyon formation (Stock and Bode, 1935). Tertiary strata on the south slope of the Avawatz Range, 10 miles south of the area of plate 7, have yielded a mammalian fauna identified by Henshaw (1939) as upper Miocene(?) or lower Pliocene(?) in age.



FIGURE 4. View northeastward across Saratoga Hills (left foreground) and Saddle Peak Hills (center), east of South Death Valley. These hills are east-tilted fault blocks, each consisting mostly of later pre-Cambrian strata of the Pahrump series. Highest part of Saddle Peak Hills is capped by lighter-colored Noonday dolomite of Lower Cambrian age. Amargosa River is on floor of South Death Valley in foreground. *Spence Air Photos.*

The most complete section of Tertiary rocks in the Death Valley region is in the northern part of the Black Mountains (figs. 5 and 6). Thayer (cited in Noble, 1941, p. 955) has estimated that this section is about 13,000 feet thick. Its lowest part probably is correlative with the Oligocene Titus Canyon formation (Stock and Bode, 1935); its higher part, consisting of Miocene and Pliocene rocks, is overlain unconformably by beds of the Pliocene-Pleistocene(?) Funeral fanglomerate. On the accompanying map (pl. 7) most of the Tertiary rocks have been grouped into the two subdivisions described below.

Included in the older Tertiary rocks are the Titus Canyon formation (Stock and Bode, 1935) and the Artist Drive formation. The Titus Canyon formation lies upon the north slopes of the Grapevine and Funeral Mountains in a narrow belt that extends into the mapped area to a point north of Chloride Cliff in the northern part of the Funeral Mountains, where it is about 1,300 feet thick and consists mostly of conglomerate, sandstone, and mudstone (Stock and Bode, 1935, p. 574). Isolated patches of similar rocks lie in and near Boundary Canyon at the north end of the Funeral Mountains and on the southern tip of the Funeral Mountains west of Death Valley Junction. A small patch lies on the south tip of Eagle Mountain, south of Death Valley Junction.

In the Black Mountains the Artist Drive formation, which is probably Oligocene in the lower part and Miocene in the upper part, has an estimated thickness of more than 5,000 feet (Thayer, cited by Noble, 1941, p. 955), and consists mostly of alternating basaltic and latitic flows, tuffs, and breccias interlayered with various sedimentary rocks. Other older Tertiary volcanic and sedimentary rocks, which appear to be at least partly correlative with the Artist Drive formation, occur in the central Black Mountains and Greenwater Range. They probably also are present as local unmapped masses in the Virgin Spring area farther south, and in a belt along the northeast base of the Avawatz Mountains.

Included in the younger Tertiary rocks are the Furnace Creek formation and the Greenwater volcanics. In the northern part of the Black Mountains the Artist Drive formation is unconformably overlain by the Furnace Creek formation (Thayer, cited by Noble, 1941, p. 956), which contains fossil leaves of probable early Pliocene age. Here the Furnace Creek formation is about 2,500 feet thick and consists mostly of volcanic rocks interbedded with fanglomerate and playa sediments that contain gypsum and borates. The lower or middle Pliocene fossil footprints in the Copper Canyon area of the central Black Mountains occur in a 3,000-foot section of folded playa beds that are similar lithologically to those of the Furnace

Creek formation in the northern part of the Black Mountains and in Furnace Creek Wash.

Intensely deformed Tertiary strata, several thousand feet thick, are discontinuously exposed in southern Death Valley from the north margin of the Avawatz Mountains (fig. 8) northwestward to the Confidence Hills (fig. 7). Although to date they have proved unfossiliferous, they resemble the playa deposits of the Furnace Creek formation and are assigned tentatively to that formation. They consist mostly of poorly consolidated mudstone and siltstone, and contain deposits of rock salt, gypsum, and celestite.

Volcanic rocks that are mostly acidic to intermediate in composition, and that contain little or no interlayered sedimentary rocks, are younger than the Furnace Creek formation and are 3,000 feet or more thick. In the Greenwater Range, these volcanic rocks crop out extensively. They are unconformable upon the Furnace Creek formation, and have been named the Greenwater volcanics and assigned a Pliocene(?) age (Thayer, cited by Noble, 1941, p. 955). Rocks of similar composition and stratigraphic position occur throughout the Black Mountains, and also are abundant at the south end of the Panamint Range north of Wingate Wash and on the northwest flank of the Owlshead Mountains south of Wingate Wash.

Pliocene-Pleistocene(?) Rocks. The Funeral fanglomerate, which probably is Pliocene in age, is widespread in the area mapped. At most places it consists of fanglomerate commonly interbedded with conspicuous black basalt flows and finer-grained sedimentary rocks. It rests unconformably upon all the older formations and, in general, is much less deformed (figs. 7 and 8; plate 8). At most places the formation is more than 1,000 feet thick. In the Virgin Spring area, the basal part of the formation contains layers of megabreccia.

South of Tecopa, the southern end of Amargosa Valley is marked by a broad, west-trending belt of low hills, underlain by beds that are tentatively correlated with the Funeral fanglomerate. These beds, which were named the China Ranch beds by Mason (1948), are moderately deformed (plate 8) and are flanked on the north and unconformably overlain by conglomeratic lake beds of Pleistocene age. The China Ranch beds are 5,000 or more feet thick and consist mostly of fanglomerate and siltstone (Wright, Map Sheet No. 17). They contain lenses and layers of megabreccia composed mostly of granitic and volcanic rocks and later pre-Cambrian and Cambrian sedimentary rocks. These megabreccias formerly were interpreted as thrust slices (Noble, 1941, p. 992), but most of them are now thought to be breccias of debris-flow origin formed down-slope from large faults and comparable to the megabreccias described by Longwell (1951, pp. 343-355).



FIGURE 5. View southeastward along east edge of Death Valley, looking up Furnace Creek Wash (center of photo). Furnace Creek Ranch is the rectangle in right foreground; Furnace Creek Inn is at mouth of wash; Black Mountains are at right of wash. This part of the Black Mountains consists of complexly folded and faulted Tertiary sedimentary and volcanic rocks, which in general dip northeast toward Furnace Creek Wash and are overlain by the Pliocene-Pleistocene (?) Funeral fanglomerate. Curved base of Black Mountain front marks the trace of Artist Drive fault. Light-colored rocks south of Furnace Creek Wash are borate-bearing beds of younger Tertiary Furnace Creek formation exposed in south limb of Furnace Creek syncline, whose axis trends northeast and lies beneath Quaternary alluvium on left of Furnace Creek Wash. *Spence Air Photos.*

Quaternary Rocks. Quaternary rocks, which are unconformable upon the Funeral fanglomerate and all older rocks, include alluvial fans, playa and lake deposits, sand dunes, and local occurrences of basaltic cinders and cinder cones. Salt, interlayered with clay, underlies at least 125 square miles of the floor of Death Valley (fig. 3 and plate 8); several holes, drilled to depths of 600 to 1,000 feet, did not penetrate its base.

TOPOGRAPHIC AND STRUCTURAL ELEMENTS

Southern Panamint Range. Although the internal structure of the southern Panamint Range is complex, the range is essentially an east-tilted fault block, bounded on the west in Panamint Valley by a major zone of normal and strike-slip faulting. Its eastern, or Death Valley face (fig. 2), partly shown on the accompanying map, consists mainly of east-dipping Paleozoic formations (see cross section, plate 8). Earlier pre-Cambrian and later pre-Cambrian (Pahrump?) metamorphic rocks compose much of the west face of the range, beyond the margin of the map (Murphy, 1932; Hopper, 1947; B. K. Johnson, personal communication, 1954; D. H. Sears, personal communication, 1954). Triassic rocks have been recognized only in the southern part of the range, west of the mapped area. East-dipping Tertiary rocks lie upon lower spurs of the range along the margin of Death Valley, but they do not occur in the high central part of the range. Bodies of granitic rocks intrude all except the Tertiary rocks.

The structure of all the Death Valley slope of the Panamint Range is imperfectly known. A mass of unmetamorphosed later pre-Cambrian (Pahrump) rocks is well exposed from Galena Canyon southward to Anvil Spring Canyon. These strata rest unconformably on older pre-Cambrian metamorphic rocks that are exposed in two windows, one in Warm Spring Canyon and the other in Galena Canyon. Numerous masses of Noonday (Lower Cambrian) dolomite rest on the Pahrump series, and post-Triassic granite cuts the Pahrump series and Paleozoic rocks in Anvil Spring Canyon. Many northwest-trending faults cut the strata of the Pahrump series. Some of them are recurrent and offset Tertiary rocks to a lesser degree. Some pre-Tertiary faults trend northeast.

North of Galena Canyon, except for the occurrence of intrusive granitic rocks near Telescope Peak just west of the map area and of Tertiary rocks on the lower spurs, the Death Valley slope is underlain entirely by Paleozoic rocks. These rocks are faulted and folded, and at some places they stand vertical, but they nearly everywhere dip eastward toward Death Valley (plate 8). Because they strike more northwestward than the trend of the mountain front, successively younger Paleozoic formations crop out northward at the valley

border. For example, the rocks at the mouth of Six Spring Canyon are the Johnnie formation; at Johnson Canyon they are the Stirling quartzite and Wood Canyon formation; north of Death Valley Canyon, Ordovician, Silurian, Devonian, and Carboniferous strata successively extend to the valley border; and the spur at Poison Spring, at the north end of the map area, is underlain by fossiliferous Permian strata.

The younger Tertiary rocks and those of the overlying Funeral fanglomerate that occur low on the spurs dip less steeply than the underlying Paleozoic rocks, and apparently they are overlain by Quaternary salt and alluvium throughout Death Valley (plate 8). They appear to be correlative with the younger Tertiary rocks and the Pliocene-Pleistocene(?) Funeral fanglomerate that cap the Black Mountains east of Death Valley. The easterly dip of the Funeral on the spurs along the Panamint front indicates that much of the tilting occurred in Pleistocene time.

Black Mountains and Greenwater Range. The Black Mountains and the Greenwater Range, together with their southern extensions—the Ibex, Saratoga, Saddle Peak, Salt Springs, and Dublin Hills—appear to form a structural unit bounded by Death Valley on the west and south and by Amargosa Valley and the lower part of Furnace Creek Wash on the east and north. In plan this unit is lozenge-shaped, and will be designated the Black Mountain wedge. It constitutes a huge fault block, about 80 miles in length and 25 miles in maximum width, that has been squeezed between the Death Valley and Furnace Creek fault zones in such a way as to produce folding and thrusting of a peculiar type.

In its general geological features the Black Mountain wedge differs markedly from the ranges that border it. It is underlain mostly by pre-Cambrian and Tertiary rocks, contains Paleozoic rocks in relatively small volume and for the most part in great disorder, and shows large folds of the pre-Cambrian basement rocks associated with low-angle faults as the most prominent features of its internal structure. In contrast, most of the bordering (Panamint, Funeral, Resting Spring, and Nopah) ranges consist largely to almost wholly of Paleozoic rocks that are much less disordered than those in the Black Mountain wedge, contain few Tertiary rocks, and are essentially east-tilted fault blocks.

Because the Paleozoic sections that occur on both sides of the Black Mountain wedge are similar in both thickness and lithology and indicate deposition on an essentially flat sea bottom, a comparable Paleozoic section, 25,000 to 30,000 feet thick, must once have overlain the entire area of the wedge. An additional 10,000 to 15,000 feet of strata, as represented by the later pre-Cambrian rocks in the southern part of the wedge and in the Panamint Range, and by the

marine and metavolcanic Triassic rocks of the Panamint Range, also may once have overlain most or all of the wedge. The missing strata indicate that a thickness of at least 25,000 feet and perhaps as much as 45,000 feet was eroded from the northern part of the wedge in the Mesozoic to early Tertiary interval as the wedge was raised along the Death Valley and Furnace Creek fault zones.

North of a line drawn through Jubilee and Sheephead Passes, the core of the Black Mountains consists of earlier pre-Cambrian gneiss and intrusive rocks. This core is discontinuously flanked and locally capped by structurally complex rock masses composed of blocks that range in age from earlier pre-Cambrian to late Tertiary. The surface of the core, against which the masses lie, is relatively smooth and has the form of large, broad folds that trend northwestward at acute angles with the north-northwest trend of the range. This surface, large parts of which have been exhumed by erosion, marks the floor of a flat thrust fault that has caused a plate of disordered blocks to override an autochthonous block that now forms the core of the range. Subsequent arching of the autochthonous block and an extensive erosional stripping of most of the plate are assumed to have produced the present surface features. These features have been studied in two adjacent areas, the Virgin Spring area (Noble, 1941) and the central Black Mountains, farther north (Curry, 1938; 1941; Contribution 7, Chapter IV).

In the Virgin Spring area the fault is a nearly continuous tectonic break that is much greater than any other break observed in the rocks above the autochthonous block. This fault, which has been named the Amargosa thrust fault (Noble, 1941, p. 961), is conceivably a feature that extends beyond the limits of the Black Mountain wedge (Noble, 1941, p. 995); but it now seems likely that it was produced by the squeezing and arching of the Black Mountain wedge under intense compression.

Most of the rocks that lie above the autochthonous block have such a disordered appearance that the term "chaos" has been applied to them (Noble, 1941, p. 964). Three phases of the chaos were recognized by Noble. The Virgin Spring phase, which everywhere rests directly on the autochthonous block, consists almost entirely of blocks whose stratigraphic range is later pre-Cambrian to Middle Cambrian, inclusive. Most of the blocks are elongate and are 200 to 600 feet long, but some are as much as half a mile long. Each block is bounded by fault surfaces and is minutely brecciated, but the original layering in most of the blocks, except those of later pre-Cambrian diabase, is discernable. The blocks commonly lie as imbricate, east-dipping slabs, crudely arranged in their normal stratigraphic succession, to form a sheet that averages about 600 feet thick. However, some adjacent blocks are derived from widely different stratigraphic horizons.

Resting on the Virgin Spring phase of the chaos are the Calico and Jubilee phases. The Calico phase is a mosaic of fault blocks composed entirely of brilliantly colored Tertiary volcanic rocks. Many high-angle faults that cut it do not cut the rocks of the autochthonous block on which it and the Virgin Spring phase rest. At some places the Virgin Spring and Calico phases appear to be separated by an unconformity of erosion, but at most places by a surface on which there has been movement. It seems probable that the movement of the Calico phase was independent of, and less than, the movement of the Virgin Spring phase and that it was separate from, though related to, the movement on the Amargosa thrust. The date of the thrusting of the Calico phase is assumed to be post-Miocene, for the rocks of this phase are those of the younger Tertiary group.

The Jubilee phase, which overlies both the Virgin Spring and Calico phases, is in part a mosaic of huge irregular fault blocks of brecciated granite and of volcanic and sedimentary rocks of Tertiary age, and in part a series of sedimentary rocks (chiefly fanglomerate) interlayered with megabreccia composed of nearly every type of rock found in the Black Mountains. Many breccia layers are formed of one type of rock. The megabreccia layers that are interbedded with the sedimentary rocks were originally interpreted as thrust slices by Noble (1941, p. 974), but he now believes that they may in part represent debris-flow accumulations developed down-slope from large faults, like the megabreccias in southern Nevada described by Longwell (1951). He believes, however, that the assemblage of huge blocks of brecciated granite and Tertiary rocks at the base of the Jubilee phase north of Ashford Mill (Noble, 1941, p. 975) represents material derived from an advancing thrust sheet. Apparently the Jubilee phase of chaos locally constitutes a basal part of the Pliocene-Pleistocene(?) Funeral fanglomerate and passes upward into the Funeral through a series of interlayered megabreccia and fanglomerate beds.

The Amargosa thrust extends northward into the central Black Mountains, where highly disordered Tertiary sedimentary and volcanic rocks rest with fault contact against the smooth surface of the autochthonous block (Curry, Contribution 7, Chapter IV). Curry has noted that the anticlinal parts of this surface resemble the carapaces of turtles and has named them "turtlebacks." He has named the three most prominent of these features, from north to south, the Badwater (fig. 3), Copper Canyon, and Mormon Point turtlebacks. The Badwater and Copper Canyon turtlebacks plunge northwestward. The Mormon Point turtleback extends southeastward into the Virgin Spring area, where it is known as the Desert Hound anticline of that area. This anticline, by far the largest of the three, is about 13 miles long and plunges at both ends. Curry

states that the entire surface of the autochthonous block of the central Black Mountains marks the position of a single thrust fault, the "turtleback fault," and he suggests that this fault is an extension of the Amargosa thrust.

South of a line drawn through Jubilee and Sheephead Passes, north-trending normal faults split the Black Mountains into four east-dipping, monoclinical fault blocks (fig. 4). These faults are cut off beneath Quaternary alluvium by the Death Valley fault zone, described below. From west to east successively younger rocks are exposed in these fault blocks. The most westerly block (Tale Ridge) is composed partly of earlier pre-Cambrian gneiss and partly of the Crystal Spring formation. The most easterly block (Salt Spring Hills) is underlain by Lower Cambrian strata and intrusive granite. In the southern part of Tale Ridge and the southern part of the Ibex Hills the later pre-Cambrian Pahrump series rests with depositional contact upon earlier pre-Cambrian gneiss. Here both Pahrump and earlier pre-Cambrian rocks are part of the autochthonous block. In the northern part of Tale Ridge and the Ibex Hills, however, the Amargosa thrust cuts across the autochthonous Pahrump and earlier pre-Cambrian rocks.

The Greenwater Range is bounded on the east by the alluviated Amargosa Valley, and is separated from the Black Mountains to the west by the continuous Furnace Creek-Greenwater Valley. The range is underlain mostly by volcanic rocks of Tertiary age. These include both older and younger Tertiary volcanic rocks, as well as basalt flows of the Funeral fanglomerate. At the south end of the range the rocks rest with depositional contact upon earlier pre-Cambrian gneiss.

The base of the Tertiary section is not exposed at the northern end of the Greenwater Range. Here steeply upturned and faulted Tertiary rocks, chiefly borate-bearing beds of the younger Tertiary Furnace Creek formation, are overlain unconformably by flat-lying basalt of the Funeral fanglomerate. At Ryan, the odd pink and green colors of the Tertiary rocks beneath the contrasting black of the basalt cap are striking scenic features. South of Ryan, the younger Tertiary rocks beneath the Funeral fanglomerate consist chiefly of the Greenwater volcanics, which at Greenwater Canyon (Thayer, cited by Noble, 1941, p. 956) are unconformable upon the Furnace Creek formation.

Basalt of the Funeral fanglomerate caps the older rocks at many places in the range. Its attitudes show that the range has been folded into a broad antiform since the Funeral was deposited, and that smaller folds are superimposed on the antiform. The Greenwater Range is traversed by a system of northeast-trending faults that neither cut the Funeral fanglomerate nor extend across the bordering Greenwater-Furnace Creek and Amargosa Valleys.

The Furnace Creek-Greenwater Valley is an alluvium-filled trough that extends southwestward from the Furnace Creek Ranch in Death Valley to the Amargosa Valley. The trough drains in opposite directions from an alluvial divide at 4,000 feet near Greenwater, Furnace Creek Valley draining northwest to Death Valley, and Greenwater Valley draining southeast to Amargosa Valley. Patches of basalt of the Funeral fanglomerate, discontinuously distributed along both sides of Greenwater Valley, dip toward its center and suggest that the trough coincides with a syncline that is probably modified by faults concealed beneath the alluvium.

Furnace Creek Valley below Ryan is excavated for the most part in complexly folded and faulted beds of the Furnace Creek formation which in general dip northeast off the Black Mountains toward the axis of the valley. Along the north side of the valley (fig. 6), the formation is in fault contact with Paleozoic rocks that underlie the south end of the Funeral Mountains. This contact marks the north edge of the northwest-trending Furnace Creek fault zone that forms the northern and eastern boundaries of the Black Mountain wedge.

The Furnace Creek fault zone is poorly exposed and the details of structure are unknown, but it is believed to be a major line of dislocation that has been recurrently active since late Mesozoic or early Tertiary time, with reversals of apparent vertical movement. Horizontal striae on vertical fault surfaces west of Echo Canyon suggest that it may have had a large horizontal as well as vertical component. The earliest movements raised the Black Mountain wedge, from which most of the Paleozoic rocks were removed during the Mesozoic-early Tertiary erosion interval. Later in the Tertiary, a reversal of movement elevated the terrane of Paleozoic rocks northeast of the wedge and determined a northwest-trending synclinal trough that extended from North Death Valley through the site of the present Furnace Creek Valley to Amargosa Valley. The Furnace Creek formation was deposited in this trough. In Pliocene time, renewed compression folded the beds in the trough and caused reverse faulting all along the northeast border of the fault zone in the Furnace Creek Valley, where, at many places, Paleozoic rocks are pushed over Furnace Creek beds. Probably the Black Mountain wedge was antiformally arched and the Amargosa and turtleback thrust faults formed during this time. Faulting accompanied by open folding took place throughout the region after the Plio-Pleistocene (?) Funeral fanglomerate had been deposited upon the Pliocene structure, and was renewed in the fault zone where it has persisted intermittently into Recent time, as is shown by reverse faults and anticlinal domes in Quaternary alluvium in the lower part of Furnace Creek Valley.



FIGURE 6. View eastward at mouth of Furnace Creek Wash. Furnace Creek Inn in foreground. Bluff upon which Inn is built marks a recent fault scarp. Behind Inn northeast-dipping beds of Funeral fanglomerate overlie similarly dipping strata of Furnace Creek formation. Ridge on skyline is composed of Lower Cambrian strata, which are in fault contact with Furnace Creek strata at Furnace Creek fault zone along base of ridge. *Spence Air Photos.*

Funeral Mountains. The geological features of the Funeral Mountains are imperfectly known, but the mountains are divisible into two structural units. The north half of the range is apparently a northwest-trending anticline whose exhumed core shows a surface that resembles the turtleback surfaces of the Black Mountains. South of Indian Pass the core of the anticline consists of weakly metamorphosed grits and thin beds of dolomite that resemble strata in the lower part of the Johnnie formation as exposed in the Trail Canyon area of the Panamint Range (Hopper, 1947). At the base of Chloride Cliff northwest of Indian Pass the rocks in the core are highly metamorphosed schist, marble, and quartz diorite gneiss that are probably pre-Cambrian in age.

In Boundary Canyon, which separates the Funeral Mountains from the Grapevine Range to the north, disordered masses of Lower Cambrian quartzite and dolomite overlie the metamorphosed rocks, and wedges of the Oligocene Titus Canyon formation (Stock and Bode, 1935) are inset by normal faulting into the Lower Cambrian rocks. Much of the northeastern flank of the range is underlain by a northeast-dipping Tertiary section composed of the Titus Canyon formation, and just beyond the north border of the map area by an overlying Pliocene (?) sequence consisting of tuffs, shales, and sandstones (Stock and Bode, 1935). The Keane Wonder fault, whose trace lies along the southwest base of the Funeral Mountains, resembles the fault along the base of the Badwater turtleback in the Black Mountains (Curry, Contribution 7, Chapter IV).

The south half of the range is underlain by Paleozoic strata in general and isolated patches of the Titus Canyon formation (Stock and Bode, 1935), which here consists chiefly of conglomerate and algal limestone. The Paleozoic strata (fig. 6) dip southeastward and have been broken by complex normal and reverse faulting. The strike of the strata, which east of the divide between Furnace Creek and Amargosa Valley are concealed beneath alluvium, is truncated by the northwest-trending Furnace Creek fault zone. Although formations are repeated several times by faulting, they are in general successively younger from northwest to southeast. For example, the rocks are Lower Cambrian at Echo Canyon, Ordovician in Pyramid Peak, and Mississippian at the southeast tip of the range near Death Valley Junction. The conspicuous white Ordovician Eureka quartzite, repeated several times by the faulting, serves as an excellent marker of the structure.

Resting Spring and Nopah Ranges. The Resting Spring and Nopah Ranges, in the eastern part of the area mapped, are separated by the alluviated Chicago Valley. They are east-tilted fault blocks composed chiefly of Cambrian strata (Hazzard, 1937; Mason, 1948), upon whose back slopes lie remnants of younger Tertiary volcanic

rocks. The ranges are essentially homoclinal but are locally cut by cross-faults, most of which trend northwestward. They also are cut by low-angle thrust faults. The frontal fault of each range lies hidden beneath alluvium. In general, the strata strike slightly more westward than the trend of the ranges, so that each range consists of successively younger formations from south to north along the frontal fault at its west base.

In the Alexander Hills, immediately south of the southern end of the Nopah Range, a 7,000-foot section of the Pahrump series overlies earlier pre-Cambrian rocks, at most places with a fault contact (plate 8). The Noonday dolomite, which overlies the Pahrump series apparently with an angular unconformity that has been modified by thrust faulting, successively cuts off units of the Pahrump series as it is traced northward through the Alexander Hills and rests upon earlier pre-Cambrian gneiss at the southern end of the Nopah Range.

Owlshead Mountains. The Owlshead Mountains, which lie southeast of the Panamint Range, are essentially a broad, flat-topped granite dome. Their position between the Death Valley fault zone on the northeast and the Garlock fault zone on the south suggests that the bulging is the result of compression between the two zones of rupture. Much of the granite is overlain by younger Tertiary volcanic rocks that probably are equivalent to the Greenwater volcanics, and by Funeral basalt and fanglomerate.

On the north flank of the dome, opposite the Confidence Hills, the granite cuts strata of the Crystal Spring formation of the later pre-Cambrian Pahrump series, which in one small exposure rests unconformably on earlier pre-Cambrian gneiss. On the south flank of the dome, north of Owl Hole Spring, the granite irregularly intrudes a complex of marble, quartzite, and schist of unknown age mapped tentatively as earlier pre-Cambrian.

The Owlshead Mountains, like the Greenwater Range, are cut by a system of northeast-trending normal faults that are post-Funeral in age. Faulting and warping have produced, in the flat summit of the dome, dry lake basins that have no exterior drainage. Faults of the northeast-trending set are truncated abruptly beneath the alluvium in South Death Valley by the Death Valley fault zone.

Death Valley Trough. The Death Valley trough consists of three segments—a northern segment, mostly outside the area mapped, that trends northwest and lies north of Furnace Creek; a middle segment that trends nearly north and extends from the mouth of Furnace Creek, opposite the north end of the Panamint Range, southward to the mouth of Wingate Wash, opposite the south end of the Panamint Range; and a southern segment that trends northwest and extends southeastward from Wingate Wash to Silurian Dry Lake, at the east

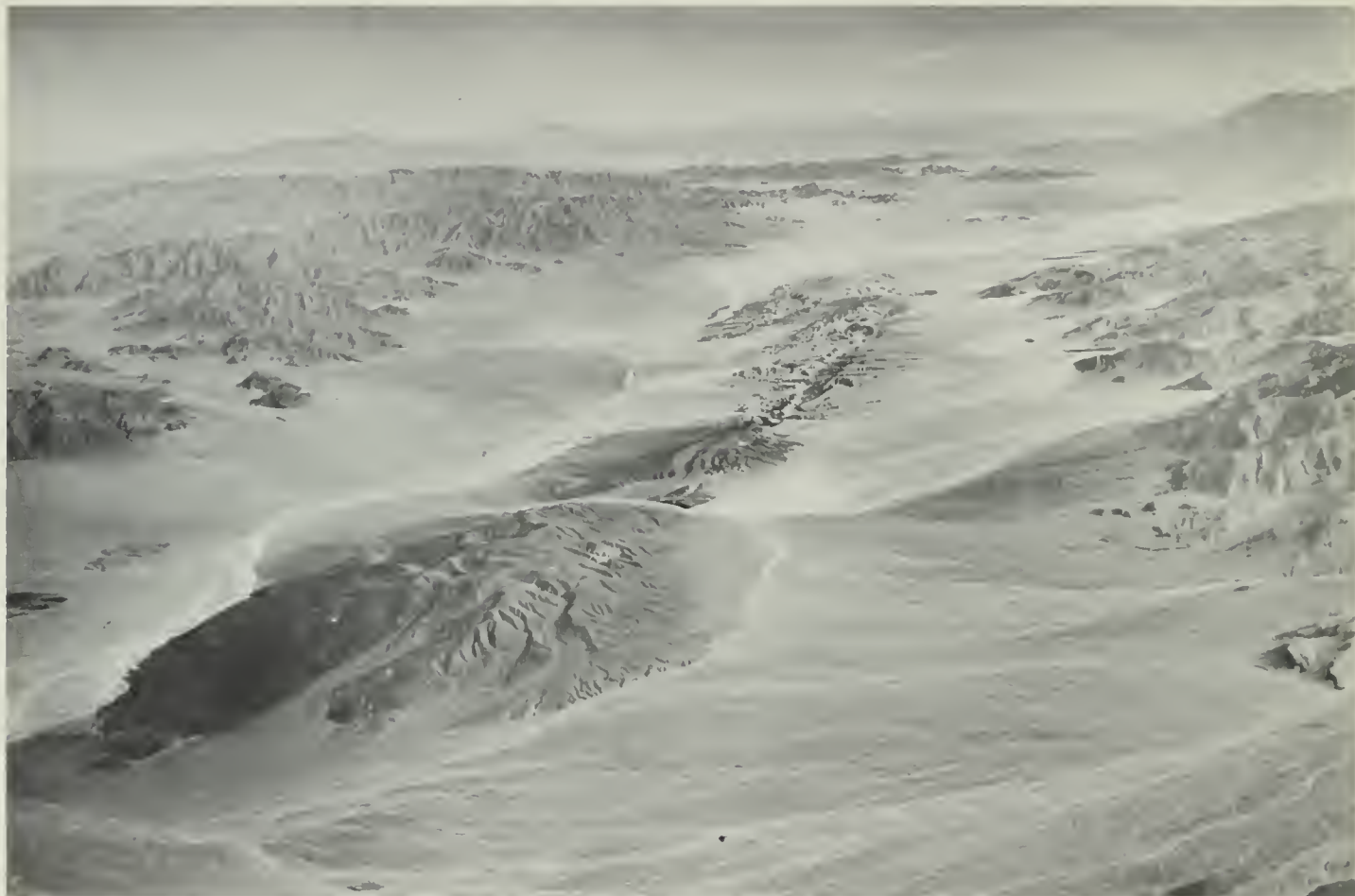


FIGURE 7. View southeastward up South Death Valley, showing Shoreline Hill (lower center) and Confidence Hills (upper center) in the Death Valley fault zone. Valley is bordered at left by southern part of Black Mountains, here underlain mostly by earlier pre-Cambrian metamorphic rocks. Lower east slope of Owlhead Mountains at right is underlain by granite cutting later pre-Cambrian strata of Pahrump series. Amargosa River lies between Confidence Hills and Black Mountains. Confidence Hills consist of tightly folded younger Tertiary strata overlain by broadly folded beds of the Pliocene-Pleistocene(?) Funeral conglomerate. Both formations are cut along west face of Confidence Hills by recent strike-slip fault in Death Valley fault zone. *Spence Air Photos.*

base of the Avawatz Mountains. The northern segment commonly is known as North Death Valley or the northern arm of Death Valley; the middle segment, which is the deepest part of the trough, constitutes Death Valley proper; and the southern segment commonly is known as South Death Valley.

During probably each of the moist intervals of Pleistocene time a lake occupied Death Valley. The largest of these lakes, named Lake Manly, probably existed during the Tahoe glacial stage (Blackwelder, 1931). It was 116 miles long and at least 600 feet deep. Shore terraces are preserved at several places in the valley, notably at Shoreline Hill, Mormon Point, and a locality about 4 miles south of Furnace Creek Inn (Blackwelder, 1933; Contribution 5, Chapter V, this volume; Clements and Clements, 1953).

North Death Valley extends northwestward from Furnace Creek for more than 50 miles, and the valley floor gradually rises to an elevation of 5,000 feet or more above sea level. It apparently marks a northwestward extension of the Furnace Creek fault zone, which is largely concealed beneath the alluvium of the valley floor. Recent movement along the zone is indicated by scarps in the alluvium at several places northwest of the mouth of Furnace Creek Wash.

Death Valley proper is a fault trough, formed largely in post-Funeral time, between the tilted Panamint Range block and the Black Mountains (plate 8). A steep fault scarp (Curry, Contribution 7, Chapter IV) forms the west face of the Black Mountains for the length of this segment of the Death Valley trough. Movement along this fault has been recurrent, probably since pre-Funeral time (Noble, 1941, pp. 989, 990). The recency of the latest faulting is shown by small scarps that break the alluvial fans and by the small volume of material in the alluvial fans at the base of the scarp, in contrast with the large volume in the huge fans extending outward from the Panamint Range (figs. 2 and 3). The fault truncates the strike of all of the Tertiary strata in the west face of the Black Mountains north of Badwater. South of Badwater, the fault follows the base of the turtleback surfaces at most places. Striae on the fault surface nearly everywhere dip 30° NW. and indicate that the movement of the block east of the fault was relatively southward and upward. This fault appears to be part of a major strike-slip zone, the Death Valley fault zone, that is assumed to lie beneath the Quaternary deposits on the floor of Death Valley proper (plate 8).

South Death Valley lies between the Owlshhead and Avawatz Mountains on the southwest and the Black Mountains on the north. The Death Valley fault zone, 2 to 4 miles wide, occupies the axis of the valley but is concealed at most places beneath Quaternary alluvium. The Confidence Hills are a long, narrow belt of tightly folded younger Tertiary rocks in the middle of the zone. Echelon folds of

similar rocks southeast of the Confidence Hills in the axis of the valley also mark the zone.

The Death Valley fault zone is well exposed just north of the Avawatz Mountains, where it contains two continuous narrow wedges composed mostly of highly brecciated pre-Tertiary rocks (fig. 8). The wedges are separated by steeply dipping faults from long, narrow belts of intensely folded younger Tertiary rocks. These structural features indicate great compression; they are similar to those that mark the San Andreas fault zone about 120 miles to the southwest (Noble, 1953, 1954). The material in the northern wedge resembles the Virgin Spring phase of chaos, and consists of blocks of the Pahump series and Noonday dolomite. The southern wedge is chiefly a megabreccia of granite, but 2 miles northwest of Sheep Creek it is a chaotic jumble of huge fault blocks of granite, red conglomeratic sandstone, and Tertiary volcanic rocks, the whole identical in lithology and structure with the part of the Jubilee phase of the chaos north of Ashford Mill, already described. At many places the faulted rocks in the zone are overlain by Funeral fanglomerate, which is itself folded and faulted, but much more gently than the pre-Funeral Tertiary rocks.

Several lines of evidence indicate that the Death Valley fault zone is a great strike-slip fault like the San Andreas and Garlock faults and that the horizontal component of movement is even greater than the vertical, although the total amount of movement is unknown. In the Confidence Hills (fig. 7) a fault in the zone has offset stream courses in such a way as to indicate that the land east of the fault zone has moved relatively southward with respect to the land on the west.

The 30° northeasterly dip of striae on the fault along the east margin of Death Valley indicates that the Black Mountain wedge east of the fault has moved relatively southward and upward. And a horizontal movement measureable in miles is suggested by the distribution of rocks of the Pahump series on opposite sides of the fault zone: rocks of the Pahump at Galena Canyon west of the fault zone lie at least 12 miles farther north than any exposures of similar rocks east of the zone.

Leach Trough from Leach Lake to Cave Spring Wash. The segment of the Garlock fault zone that extends from Leach Lake eastward to Cave Spring Wash marks the easternmost part of Leach trough. Here the Garlock fault zone is structurally similar to the Death Valley and San Andreas fault zones, and consists of long, narrow wedges of brecciated pre-Tertiary rocks separated by faults from belts of complexly folded Tertiary rocks, the whole overlain unconformably by the Funeral fanglomerate, which is itself faulted and gently folded and the folds arranged in echelon. The brecciated



FIGURE 8. View southeastward in South Death Valley along Death Valley fault zone (center foreground) showing junction of Death Valley and Garlock fault zones at north base of Avawatz Mountains (crest of mountains is skyline in background). Cave Spring Wash crosses Garlock fault zone at right of view and crosses Death Valley fault zone at center of view. Death Valley fault zone consists of parallel slivers bounded by high-angle reverse faults. One sliver (A) is composed mostly of disordered blocks of the later pre-Cambrian Crystalline Spring formation that resemble the Virgin Spring phase of chaos. Another sliver (GR), which consists of blocks of granite, conglomeratic sandstone, and volcanic rocks, resembles the Jubilee phase of chaos. These are interlayered with slivers of highly folded younger Tertiary sedimentary rocks (TY). Funeral conglomerate (TF) overlies all the older rocks and is broadly folded. *Spence Air Photos*.

wedges, however, contain no rocks identifiable as belonging to the Pahrump series, and in this respect they differ from the wedges in the Death Valley fault zone.

That the land south of the Garlock fault zone has moved 8 to 12 miles eastward with respect to the land north of the fault is suggested by the fact that the marble-bearing earlier pre-Cambrian (?) rocks near Owl Hole Spring in the Owshead Mountains north of the zone match similar rocks at Cave Spring Wash, within the zone. Four miles southeast of Owl Hole Spring and lying just north of the Leach Lake fault in the Garlock fault zone, a wedge of huge, chaotic fault blocks is exposed for about 6 miles. The blocks, most of them hundreds of feet in diameter, are granite, metavolcanic, and schistose rocks like autochthonous rocks that crop out south of the Garlock fault zone several miles southeast of the wedge. This apparent offset of lithologically similar rocks also suggests horizontal movement on the Garlock fault zone.

The Death Valley and Garlock fault zones meet in a small, alluvium-covered area just west of Sheep Creek, so that their relations one to the other are concealed. They meet at an angle so acute that it is impossible to be certain whether one fault zone is cutting the other or whether they are contemporaneous. Both are recurrent faults. If the largest horizontal movement on the Death Valley fault zone is more recent than that on the Garlock, the curvature of the Garlock fault zone toward the Death Valley fault zone may be the result of drag on the Death Valley fault zone.

Owl Hole Wash. Owl Hole Wash is an alluvial embayment between the Garlock fault zone on the south, the Owshead Mountains on the north, and the Death Valley fault zone on the northeast. Underlying the alluvium are poorly exposed folded and faulted Tertiary rocks whose structure is exceedingly complex, apparently because they form a wedge tightly pinched between the two fault zones.

Wingate Wash. Wingate Wash, lying between the Owshead Mountains on the southeast and the southern end of the Panamint Range on the northwest, coincides with a syncline in younger Tertiary volcanic rocks and the unconformably overlying Funeral fanglomerate. The volcanic rocks probably are equivalent in age to the younger Tertiary Greenwater volcanics. South of the wash they dip northwestward from the granitic dome of the Owshead Mountains. The overlying fanglomerate dips less steeply. North of the wash the volcanic rocks are complexly folded, but at most places they dip toward the wash. At the mouth of the wash are exposures of algal limestone of Tertiary age whose relation to the volcanic rocks is undetermined but which probably represent a sedimentary part of the

younger Tertiary Furnace Creek formation. In late Pleistocene time, Wingate Wash is believed to have carried to Death Valley the glacial drainage that formed lakes in Owens, Searles, and Panamint Valleys.

Amargosa Valley. The Amargosa Valley is a north-trending, alluvium-filled trough between the Greenwater Range and the Dublin Hills on the west, and the Resting Spring Range on the east. It is assumed to coincide with the southern extension of the Furnace Creek fault zone, although for most of its length it is hidden beneath Quaternary alluvium. Hot springs in the lower Furnace Creek Valley and at Shoshone and Tecopa in Amargosa Valley are aligned along the fault zone, and rocks of pre-Tertiary age that are locally exposed within the zone south of Tecopa are highly shattered.

Remnants of basalt of the Funeral fanglomerate lie on the ranges bordering the Amargosa Valley on the west, and extend to the valley floor at Shoshone. After the Funeral was deposited, the valley was depressed by faults along the base of the Resting Spring Range, and a Pleistocene lake occupied the southern end of the valley between Shoshone and Tecopa, where its partly dissected, essentially horizontal beds cover a wide area on the floor of the valley.

REFERENCES

- Axelrod, D. I., 1940, A record of *Lyonothamnus* in Death Valley: Jour. Geology, vol. 48, pp. 526-531.
- Ball, S. H., 1907, A geologic reconnaissance in southwestern Nevada and eastern California: U. S. Geol. Survey Bull. 308, 218 pp.
- Blackwelder, Eliot, 1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geol. Soc. America Bull., vol. 42, pp. 865-922.
- Blackwelder, Eliot, 1933, Lake Manly, an extinct lake in Death Valley: Geog. Rev., vol. 23, pp. 464-471.
- Blackwelder, Eliot, 1954, Pleistocene lakes and drainage in the Mojave region, southern California: Contribution 5, Chapter V, this volume.
- Clements, Thomas, and Clements, Lydia, 1953, Evidence of Pleistocene man in Death Valley, California: Geol. Soc. America Bull., vol. 64, pp. 1189-1204.
- Curry, H. D., 1938, "Turtleback" fault surfaces in Death Valley, California (abstract): Geol. Soc. America Bull., vol. 49, p. 1875.
- Curry, H. D., 1941, Mammalian and Avian ichnites in Death Valley (abstract): Geol. Soc. America Bull., vol. 52, p. 1979.
- Curry, H. D., 1954, "Turtlebacks" in the central Black Mountains, Death Valley, California: Contribution 7, Chapter IV, this volume.
- Durrell, Cordell, 1953, Geological investigations of strontium deposits in southern California: California Div. Mines Special Rept. 32, 48 pp.
- Gale, H. S., 1913, Prospecting for potash in Death Valley, California: U. S. Geol. Survey Bull. 540-N, pp. 11-19.
- Gale, H. S., 1915, Salines in the Owens, Searles, and Panamint basins, southeastern California: U. S. Geol. Survey Bull. 580-L, pp. 251-323.
- Hazzard, J. C., 1937, Paleozoic section in the Nopah and Resting Springs Mountains, Inyo County, California: California Jour. Mines and Geology, vol. 33, pp. 273-337.
- Hazzard, J. C., 1951, Revision of Devonian and Carboniferous sections, Nopah Range, Inyo County (abstract): Geol. Soc. America Bull., vol. 62, p. 1503.

- Henshaw, P. C., 1939, A Tertiary mammalian fauna from the Avawatz Mountains, San Bernardino County, California: Carnegie Inst. Washington Pub. 514, pp. 1-30.
- Hewett, D. F., 1940, New formation names to be used in the Kingston Range of the Ivanpah quadrangle, California: Washington Acad. Sci. Jour., vol. 30, pp. 239-240.
- Hopper, R. H., 1947, Geologic section from the Sierra Nevada to Death Valley, California: Geol. Soc. America Bull., vol. 58, pp. 393-432.
- Kapfer, D. H., 1954, Geology of the Silurian Hills, San Bernardino County, California: Map Sheet No. 19, this volume.
- Longwell, C. R., 1951, Megabreccia developed down slope from large faults: Am. Jour. Sci., vol. 249, pp. 343-355.
- Mason, J. F., 1948, Geology of the Tecopa area, southeastern California: Geol. Soc. America Bull., vol. 59, pp. 333-352.
- McAllister, J. F., 1952, Rocks and structures of the Quartz Spring area, northern Panamint Range, California: California Div. Mines Special Rept. 25, 38 pp.
- Muehlberger, W. R., 1954, Geology of the Quail Mountains, San Bernardino County, California: Map Sheet No. 16, this volume.
- Murphy, F. Mae, 1932, Geology of a part of the Panamint Range, California: California Div. Mines Rept. 28, pp. 329-356.
- Noble, L. F., et al., 1922, Nitrate deposits in the Amargosa region, southeastern California: U. S. Geol. Survey Bull. 724, 99 pp.
- Noble, L. F., et al., 1931, Nitrate deposits in southeastern California: U. S. Geol. Survey Bull. 820, 108 pp.
- Noble, L. F., 1937, Sketch of the geology of Death Valley, California, Death Valley National Monument booklet.
- Noble, L. F., 1941, Structural features of the Virgin Spring area, Death Valley, California: Geol. Soc. America Bull., vol. 52, pp. 941-1000.
- Noble, L. F., 1953, Geology of the Pearland quadrangle, California: U. S. Geol. Survey, Geol. Quad. Map GQ 24.
- Noble, L. F., 1954, Geology of the Valerme quadrangle, California: U. S. Geol. Survey, Geol. Quad. Map GQ 50.
- Nolan, T. B., 1929, Notes on the stratigraphy and structure of the northwest portion of Spring Mountain, Nevada: Am. Jour. Sci., 5th ser., vol. 17, pp. 461-472.
- Ransome, F. L., Emmons, W. H., and Garrey, G. H., 1910, Geology and ore deposits of the Bullfrog district, Nevada: U. S. Geol. Survey Bull. 407, 130 pp.
- Sears, D. H., 1953, Origin of Amargosa chaos, Virgin Spring area, Death Valley, California: Jour. Geology, vol. 61, pp. 182-186.
- Stock, Chester, and Bode, F. D., 1935, Occurrence of lower Oligocene mammal-bearing beds near Death Valley, California: California Acad. Nat. Sci., vol. 21, pp. 571-579.
- Ver Planck, W. E., 1952, Gypsum in California: California Div. Mines Bull. 163, 151 pp. Contains geologic map of Avawatz Mountains gypsum and salt deposits by H. R. Johnson and J. O. Lewis.
- Wright, L. A., 1949, Crystal Spring formation, southern Death Valley area (abstract): Geol. Soc. America Bull., vol. 60, p. 1948.
- Wright, L. A., 1952a, Geology of the Superior tale area, Death Valley, California: California Div. Mines Special Rept. 20, 22 pp.
- Wright, L. A., 1952b, Contact-metamorphism along pre-Cambrian diabase sills of the Death Valley region, California (abstract): Geol. Soc. America Bull., vol. 63, p. 1347.
- Wright, L. A., 1954, Geology of the Alexander Hills area, Inyo and San Bernardino Counties, California: Map Sheet No. 17, this volume.

O