2. GEOLOGY OF THE IMPERIAL VALLEY REGION, CALIFORNIA

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This report is a geologic summary of detailed field work done by the writer in 1943 and 1944 under the direction of Rollin W. Eckis and Harold W. Hoots. Eckis had mapped an area in the southeastern Santa Rosa Mountains and Clark Valley as a thesis problem in 1931. The writer is indebted to Richfield Oil Corporation for permission to publish this report, to Rollin W. Eckis and to Mason L. Hill for criticism of the manuscript, and to Joseph Ernst of the Texas Company for information and discussion.

The Imperial-Coachella Valley is a broad, flat, alluviated area that lies partly below sea level. It is cut off from the Gulf of California to the south by the Colorado River delta. The lowest part of the valley is flooded by the Salton Sea, an inland lake 240 feet below sea level that serves as the sump for all drainage within the mapped region.

For purposes of the following geologic discussions, the Imperial Valley region can be divided into three general areas. These are: (1) northeastern Coachella Valley, including the Indio and Mecca Hills, and Durmid Hill northeast of Salton Sea; (2) northwestern Imperial Valley, including the Superstition Hills, San Felipe Hills west of Salton Sea, rising northwestward to the Santa Rosa Mountains, Borrego Mountain and Badlands, and Borrego and Clark Valleys; and (3) southwestern Imperial Valley, including the Yuha desert area, Coyote Wells Valley, Coyote Mountains, Carrizo-Vallecito Valley, and Fish Creek-Vallecito Granite Mountains.

STRATIGRAPHY

Pre-Tertiary Rocks

The Chuckwalla complex, named by Miller (1944) from the Little San Bernardino and Cottonwood Mountains, is of supposed pre-Cambrian age, and is composed of gneiss intricately intruded by hornblende diorite and leuco-granitic rocks.

The Orocopia schist, named by Miller (1944), is a dark gray mica schist of supposed pre-Cambrian age. Many thousands of feet of this rock are exposed in the Orocopia Mountains, and the schist extends westward under the Tertiary sediments of the Mecca Hills.

Unnamed metasediments of Paleozoic (?) age, composed of dark-colored biotite schist and interbedded white limestone, crop out in the Santa Rosa Mountains where a thickness of possibly 20,000 feet is exposed. The series is metamorphosed to gneiss and marble where it lies within or adjacent to granitic intrusive rocks.

In the Carrizo Peak area of the Coyote Mountains is exposed about 10,000 feet of gray mica schist and gray to white limestone of Paleozoic (?) or Triassic (?) age. Southward and westward from Carrizo Peak this series is increasingly metamorphosed to gneissoid granitic rocks at the southeast and west ends of the Coyote Mountains. The schist appears to have been granitized in place, and the limestone lentils have been recrystallized to marble.

In parts of the Fish Creek Mountains, and in the foothills of the Peninsular Ranges southwest and south of Coyote Wells, is a series of gneisses, gneissoid granites, and scattered lentils of marble. These rocks probably are the same as the schist-limestone series of the Coyote Mountains, but represent a more highly advanced stage of metamorphism.

Hornblende-rich diorite, with facies of quartz diorite and gabbro, are the dominant intrusive rocks of the low mountains within the Imperial Valley region, such as Signal Mountain, Superstition Mountain, Fish Creek-Vallecito Mountains, Borrego Mountain, and the eastern foothills of the Santa Rosa Mountains.

Granodiorite and subordinate granite, quartz monzonite, and quartz diorite are the dominant rock types of the Peninsular Ranges, where they form parts of the southern California batholith of probable Cretaceous age (see Larsen, Contribution 3, Chapter VII). These rock types extend northward through Granite Mountain, the mountains west of Borrego Valley, and into the San Jacinto Mountains. From the San Jacinto Mountains sill-like wedges of the granitic rocks extend southeastward into the metasediments of the Santa Rosa Mountains. The granitic rock types appear to intrude both the metamorphic and dioritic rocks to the east, and evidently crystallized from great masses of acidic magmas.

Granite pegmatite occurs as numerous subparallel dikes in the igneous and metamorphic rocks in the Peninsular Ranges and in Granite Mountain, and extend as far east as the Coyote and Fish Creek Mountains. Pegmatites of intermediate to basic composition are present, as well (see Jahns, Contribution 5, Chapter VII).

Cenozoic Rocks

The irregular surface of erosion developed on the crystalline rocks is overlain by a great thickness of Cenozoic clastic sediments that fill the Imperial depression and were derived from the adjacent mountain areas and from the drainage area of the Colorado River. The series represents essentially continuous deposition since Miocene time, and attains a maximum exposed thickness of 16,500 feet in

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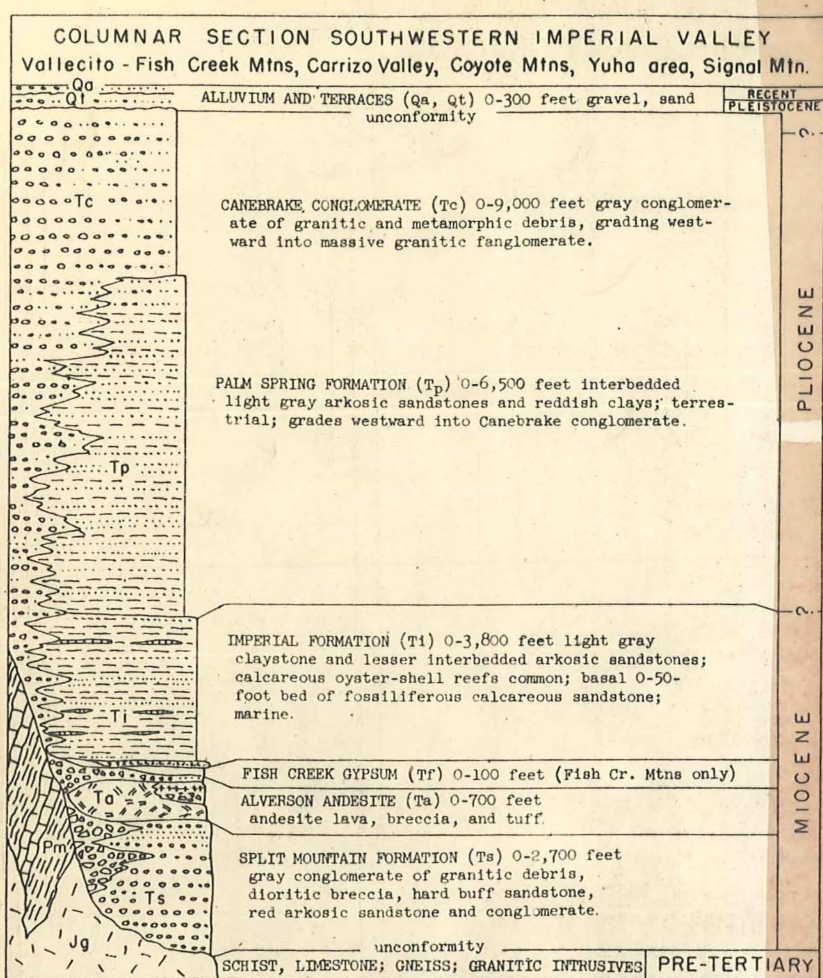

FIGURE 1. Columnar section for southwestern Imperial Valley.

southwestern Imperial Valley, 18,700 feet in northwestern Imperial Valley, and 8,600 feet in northeastern Coachella Valley. Seismic data suggest that the sedimentary fill is more than 20,000 feet thick in Imperial and Coachella Valleys. The Cenozoic sediments accumulated in a trough that connected with the Gulf of California, but not with any of the California coastal basins.

Cenozoic Stratigraphy of Southwestern Imperial Valley. The Split Mountain formation, named by Tarbet (1944), is essentially a coarse basal conglomerate of Miocene age that is present only locally on an irregular surface cut on the older crystalline rocks. It is conformably overlain by younger formations. At the type locality in Split Mountain Gorge, south of Ocotillo, the formation is about 2,700 feet thick and is composed of basal red and gray granitic fanglomerate, sandstone, and dioritic breccia at the top. The formation thins out southeastward, and is present in the Coyote Mountains at only two localities. It is widespread south of Coyote Wells Valley, where it appears as granitic fanglomerate.

The Alverson andesite lava is a dark brown basic andesite of probable upper Miocene age that overlies the Split Mountain conglomerate and the older "basement" rocks in the western foothills of Coyote Wells Valley, in the Coyote Mountains, and in the Fish Creek Mountains. The lava is about 400 feet thick at Alverson Canyon, the type locality, and about 700 feet thick at the east end of the Coyote Mountains, where it is associated with tuff and breccia.

The Fish Creek gypsum is a playa deposit of white, bedded gypsum and anhydrite that rests on the Split Mountain conglomerate and is overlain by the Imperial formation in the western Fish Creek Mountains. It ranges in thickness from a knife edge to about 100 feet. A part of this extensive deposit is being quarried by the United States Gypsum Company (Ver Planck, 1952). The most northwesterly exposure contains celestite at the top (Durrell, 1953).

The Imperial formation, named by Woodring (1931), is a series of marine clays and sandstones that lie with essential concordance on the Alverson lava, the Split Mountain formation and the Fish Creek gypsum, or in some areas, unconformably on the "basement" rocks. They grade upward into the Palm Spring formation. The Imperial beds are extensively exposed from the Fish Creek Mountains southeastward to the northwest foothills of Signal Mountain, across the Mexican border. The section is composed of gray, yellow-weathering claystone; interbedded buff sandstone and dark, calcareous, oyster-shell reefs; and a basal calcareous or sandy bed that contains numerous mollusks and some corals. The claystone contains Foraminifera, ostracods, and diatoms. The fauna of the Imperial formation is of the shallow marine gulf type, and indicates an upper Miocene or possibly a lower Pliocene age (see Durham, Contribution 4, Chapter III).

At the type area on the south side of Carrizo Valley, the Imperial formation is about 2,500 feet thick, and it thins out westward. On the north side of the valley at Fish Creek Wash, it is about 3,700 feet thick. On the east and south sides of the Coyote Mountains, the formation is about 2,700 feet thick, and it lenses out west of Coyote Wells. At Yuha Buttes the uppermost 1,000 feet of the Imperial formation is exposed, and west of Signal Mountain the formation is 500 feet to 1,500 feet thick.

The Palm Spring formation, named by Woodring (1931), is a thick series of land-laid arkosic sandstones and red clays of Pliocene age. It grades downward into the marine Imperial formation, upward and westward into the Canebrake conglomerate, and is exposed extensively from Carrizo Valley southeastward to Signal Mountain. The Palm Spring formation was deposited throughout the Imperial depression after marine waters of the Gulf were barred from it, probably by the damming action of the Colorado River delta. Fragments of silicified wood, chiefly ironwood, are common throughout the formation.

The Palm Spring formation is about 4,800 feet thick at the type locality, on the south side of Carrizo Valley, and it thins westward. On the north side of Carrizo Valley it thickens to about 6,500 feet at Fish Creek Wash, thence eventually grades westward into the Canebrake conglomerate.

The Canebrake conglomerate, named after Canebrake Wash, is the coarse marginal conglomerate facies of the Palm Spring and Imperial formations. The type section is at the southeastern base of Vallecito Mountain, 3 miles west of Fish Creek Wash, where the conglomerate is about 7,000 feet thick. The most westerly exposures are fanglomerate that laps onto and against the crystalline "basement" rocks. Southeastward along the strike, the lower 4,000 feet of the conglomerate grades into the Imperial and Palm Spring formations, and the upper 3,700 feet persists basinward into Carrizo Valley as a gray pebble and cobble conglomerate that rests on the Palm Spring formation. This conglomerate thins to about 2,500 feet on the south side of Carrizo Valley, and to 2,000 feet on the south side of the Coyote Mountains.

Cenozoic Stratigraphy of Northwestern Imperial Valley. Conglomerate and sandstone of the Split Mountain formation crop out only at a very small exposure on the north flank of Superstition Mountain, where they are about 200 feet thick. In the San Felipe Hills this formation was encountered beneath the Imperial formation in three deep wells. On the peak southeast of the Santa Rosa Mountains, it may be represented by diorite-rich breccia.

The Imperial formation is partially exposed in the San Felipe Hills, and was penetrated in that area by three deep wells in which a total thickness of about 3,600 feet is indicated. In the isolated low hills north of Ocotillo, the basal part of the Imperial formation is exposed immediately above a biotite schist. Westward and northwestward the Imperial formation laps out against "basement" rocks. It is not present in Borrego Mountain nor in the Santa Rosa Mountains, except for about 50 feet of fossiliferous sandstone a mile southwest of Travertine Point near Salton Sea.

The Palm Spring formation is extensively exposed throughout the San Felipe Hills and westward into Borrego Valley, where it grades downward into the Imperial marine beds and upward into the

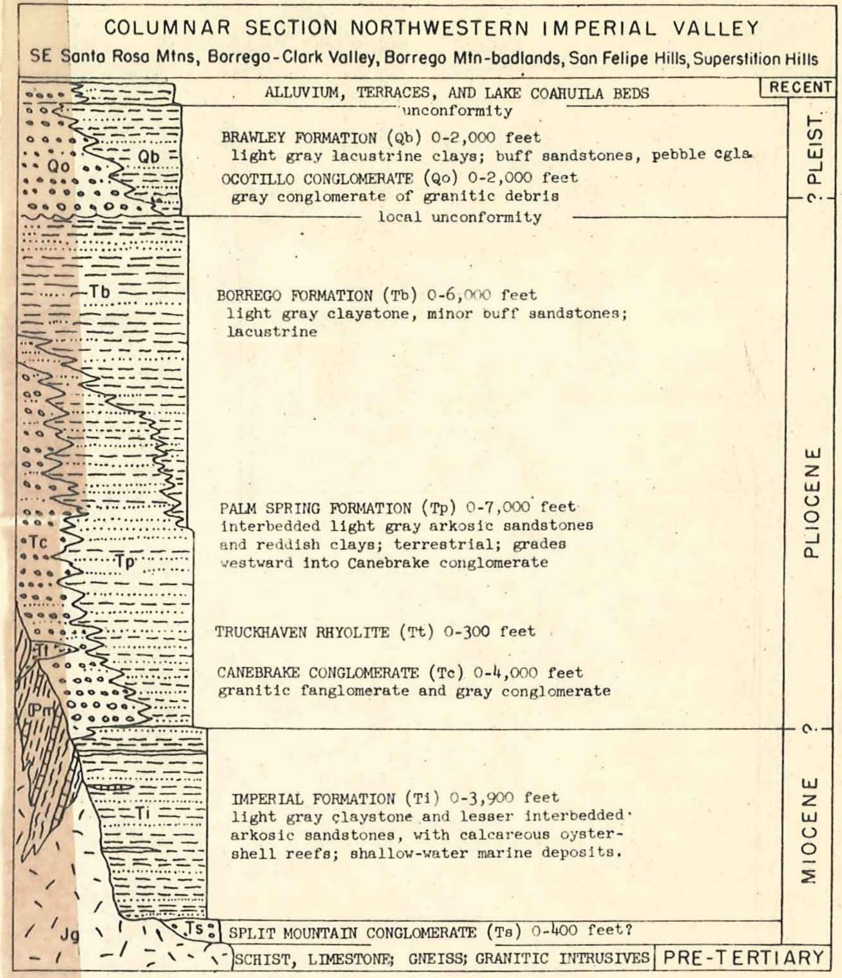

FIGURE 2. Columnar section for northwestern Imperial Valley.

Borrego lacustrine beds. The formation attains its maximum thickness of 7,100 feet in the Borrego Badlands. It thins eastward to 6,800 feet on the north flank of the San Felipe Hills anticlinorium, and to 3,600 feet or less on the east-plunging nose and the south flank of this structural feature.

The Canebrake conglomerate is the coarse marginal facies of the Palm Spring formation, as in the Carrizo Valley area. At the southeast end of the Santa Rosa Mountains, the entire thickness of the Palm Spring red beds that are exposed west of Salton Sea grades laterally westward into granitic conglomerate of the Canebrake facies, which rests on crystalline rocks and extends far up the slopes of the Santa Rosa Mountains as fanglomerate. In Borrego Mountain the lower part of the Palm Spring formation is represented by the Canebrake conglomerate facies.

The Truckhaven rhyolite crops out near Truckhaven, west of Salton Sea, where the lava forms a lens of varicolored felsitic rock that was extruded along an adjacent east-west fault. The lens is 100 feet in maximum thickness, and wedges out southward into the Canebrake conglomerate.

The Borrego formation, named by Tarbet (1944), is of probable upper Pliocene age. It has been mapped by the writer as the lacustrine facies of the terrestrial Palm Spring formation, and is composed of light gray claystone and interbedded sandstone. The claystone contains a lacustrine fauna of minute mollusks, ostracods, and rare Foraminifera. Fragments of petrified wood are rare. In the Borrego Badlands, the type section, the Borrego lake beds grade downward into terrestrial beds of the Palm Spring facies, and are overlain by the Ocotillo conglomerate.

The Borrego formation attains its maximum thickness of about 6,000 feet in the Borrego Badlands, and thins westward to only 2,000 feet at the west edge of this area. It thins eastward to 2,900 feet on the north flank of the San Felipe anticlinorium, to 2,000 feet on the east plunge of that feature, and on the south flank of the anticlinorium it is overlapped by the Ocotillo conglomerate.

The Ocotillo conglomerate overlies the Borrego lacustrine clays, and, together with the Brawley lake bed facies into which the conglomerate grades, forms the youngest unit of the Cenozoic series in Imperial Valley. It is either upper Pliocene or lower Pleistocene in age. The type section is in the northern part of the Borrego Badlands northeast of Borrego, where the formation is composed of about 800 feet of gray granitic-pebble conglomerate that lies conformably upon the Borrego clays. The Ocotillo conglomerate, as exposed near Ocotillo and eastward on the south flank of the San Felipe Hills anticlinorium, is about 1,000 feet thick and lies unconformably upon the Borrego clays. Northeastward from Ocotillo, it overlaps onto the Palm Spring and Imperial formations. Eastward in the San Felipe Hills, the conglomerate grades laterally and basinward into the Brawley lacustrine beds.

The Brawley formation is the lacustrine and continental basinward facies of the Ocotillo conglomerate, and is lithologically very similar to the underlying Borrego lake beds. The type section of this formation is just west of U. S. Highway 99 and west of the south end of Salton Sea, where about 2,000 feet of light gray claystone and thin interbeds of buff sandstone is exposed. The clays contain a minute lacustrine fauna like that of the underlying Borrego clays.

In the Superstition Hills the Brawley formation is composed of lacustrine and terrestrial clays, sands, and pebble gravels, and the base is not exposed. Around Superstition Mountain the Brawley formation, the basal portion of which is the Ocotillo conglomerate facies, unconformably overlaps the Imperial formation, Alverson lava, and the Split Mountain formation onto diorite. Southeastward and adjacent to the Superstition Mountain fault, the Ocotillo-Brawley series lies unconformably on the Borrego clays, and an angular discordance of as much as 60° is exposed north of the fault.

Cenozoic Stratigraphy of Northeastern Coachella Valley. The Dos Palmas rhyolite crops out in the Mecca Hills, 8 miles S. 30° E. of Mecca, and is of probable Miocene age. It rests directly upon much older crystalline rocks.

The Mecca formation is essentially a basal conglomerate of granitic and metamorphic debris that lies upon the "basement" rocks and is overlain by the Palm Spring formation in the Mecca and Indio Hills. It correlates with either the Split Mountain formation or the basal Canebrake conglomerate. The type section of the Mecca conglomerate is on the Mecca Hills anticline at Painted Canyon, 5 miles northeast of Mecca, where the conglomerate is about 400 feet thick. Two miles northwest of Painted Canyon, the upper part of the formation contains reddish sands and clays, and in another exposure a mile farther north, the conglomerate contains cobbles of sandstone with marine Eocene fossils. On the Mecca Hills anticline, 3 miles southeast of Painted Canyon, the Palm Spring formation is unconformably underlain by about 600 feet of the Mecca formation, which here consists of hard, pinkish gray sandstones and reddish clays. The base is not exposed.

The Imperial formation crops out only in the northwestern Indio Hills, where only the uppermost part of the fossiliferous, yellow-weathering clays is exposed beneath the Palm Spring and Ocotillo formations. On the south side of a low hill near Garnet, 12 miles northwest of Edom, 50 feet of fossiliferous sandstone questionably assigned to the Imperial formation lies unconformably beneath the Ocotillo conglomerate.

The Palm Spring formation crops out in both the Indio and Mecca Hills, where it consists of superbly exposed red to buff arkosic sandstones and thin interbeds of reddish to greenish clays. In the northwestern Indio Hills the formation is about 2,000 feet thick and overlies the Imperial marine clays, and in the southeastern Indio Hills it is about 3,300 feet thick and overlies the Mecca conglomerate. In the Mecca Hills east of the San Andreas fault, the Palm Spring formation is about 4,800 feet thick, lies above the Mecca formation, and grades eastward into the Canebrake conglomerate facies. West of the fault only the uppermost 1,500 feet of the Palm Spring for-

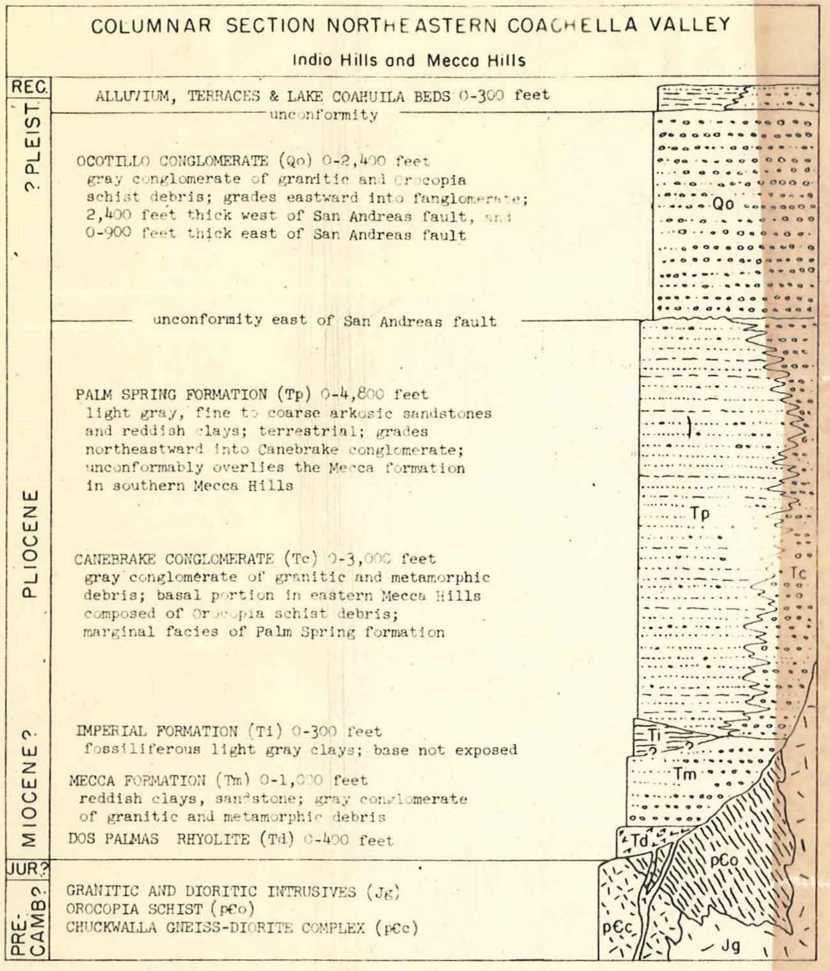

FIGURE 3. Columnar section for northeastern Coachella Valley.

mation is exposed. Here it consists of red clays and white arkosic sandstones. Near Durmid, east of the fault, the uppermost 1,500 feet of the Palm Spring formation is exposed, and consists of hard, pinkish gray sandstone.

The Canebrake conglomerate facies of the Palm Spring formation is partly exposed in the southeastern Indio Hills, where the sandstones of the Palm Spring formation grade northward into it. The conglomerate is difficult to distinguish from the overlying Ocotillo conglomerate. In the eastern Mecca Hills, the Palm Spring sandstones grade eastward into the Canebrake conglomerate, which is composed of granitic and metamorphic debris. This conglomerate laps onto the Orocopia schist. Southeast of Box Canyon the basal part of the Canebrake conglomerate rests upon the Dos Palmas rhyolite, and is composed entirely of Orocopia schist debris.

The Ocotillo conglomerate crops out extensively in both the Mecca and Indio Hills. It is of the same facies and probably is of the same age as the Ocotillo conglomerate west of Salton Sea. It is the youngest formation of the Cenozoic series exposed in the hills northeast of Coachella Valley, and probably is of upper Pliocene or lower Pleistocene age. The conglomerate is a piedmont alluvial fan deposit of granitic and metamorphic debris derived from the mountains to the northeast. The top is a surface of deposition, which is undisturbed at the foot of the mountains but which becomes increasingly deformed and eroded as traced westward in the Mecca and Indio Hills. In the Mecca Hills east of the San Andreas fault, the conglomerate ranges in thickness from a knife edge to 900 feet, and lies unconformably on older formations. West of the fault it is about 2,500 feet thick and overlies the Palm Spring red beds. On both sides of the fault the conglomerate contains a large percentage of Orocopia schist debris. In the Indio Hills the Ocotillo conglomerate is about 2,100 feet thick. It lies unconformably on the Canebrake, Palm Spring, and Imperial formations, and shows a northwestward overlap.

In the Durmid area, northeast of Salton Sea, about 6,100 feet of lacustrine beds of the Borrego-Brawley facies is upended and contorted on the southwest side of the San Andreas fault. Near Bertram the lowest 1,200 feet of these beds is composed of hard, buff sandstones and interbeds of gray claystone; it may be equivalent to the Palm Spring formation but appears to be of lacustrine origin. These beds are overlain by about 2,700 feet of light-gray, thin-bedded claystones that contain thin sandy beds and many layers, as much as five feet thick, of white salines, chiefly sodium sulfate (Sampson and Tucker, 1942). This last-named section probably correlates with the type Borrego formation. The beds are overlain by about 2,200 feet of light gray claystone with a small amount of sandstone, which are exposed along the shore of Salton Sea. They are similar to, and may correlate with, the type Brawley lacustrine beds. No superjacent formation is present in this area.

Stratigraphy of Imperial Valley Proper. In recent years several deep wells were drilled for oil in the flat, alluviated portion of Imperial Valley. The deepest of these was drilled to 12,313 feet near Holtville, another to 8,350 feet near Westmoreland, another to 7,323 feet near Heber, and still another to 8,647 feet in the Superstition Hills. All encountered nonmarine sands and clays, from top to bottom, with some lacustrine beds in the uppermost 3,000 feet. The marine Imperial formation either was not reached in any of these wells, or is represented in the section by deltaic sediments deposited by the Colorado River.

GEOLOGIC STRUCTURE

Northeastern Coachella Valley

San Andreas Fault Zone. The San Andreas fault follows a uniformly straight course through the Indio Hills southeastward to the northeast shore of Salton Sea. It probably is vertical or nearly so. In the Indio Hills the fault comprises two branches that merge southeastward. Both branches form low scarps that generally face northeastward in the northwest part of the hills and southwestward in the southeast part, which suggest that the hills have been sliced by right lateral movement on the fault.

Throughout the course of the fault right lateral movement, or relative southeastward displacement of the northeast block, is indicated by several offset washes and by sharp east-trending drag folds in the adjacent Cenozoic sediments. The sediments near the fault are invariably upended, contorted, or sheared. The total horizontal displacement since Pliocene time probably amounts to several miles, as the stratigraphically equivalent rocks on either side of the fault in the Mecca and Durmid Hills differ markedly.

In the Mecca Hills, northeast of the San Andreas fault, are several steeply dipping faults that are nearly parallel to and related to the San Andreas. Each shows upward and probable northwesterly displacement of the block southwest of it.

Folding in the Cenozoic Sediments. The Indio Hills is a large anticlinal upwelling of the Coachella Valley sedimentary fill along the San Andreas fault zone. The northwestern and southeastern parts of the hills are anticlinal, with axes that trend approximately N. 70° W. In the Mecca Hills, the Palm Spring formation on the west side of the fault is upended and wrinkled into tight folds that trend N. 70° W, and the overlying Ocotillo conglomerate is tilted steeply valleyward. East of the fault the Tertiary sediments are compressed into the large Mecca Hills anticlinal uplift, and sheared Orocopia schist is exposed at the structurally highest point in Painted Canyon. In the axial portion of this fold the sediments are buckled into numerous tightly compressed minor folds that are arranged en echelon and trend N. 75° W. as compared to the N. 50° W. trend of the major fold axis and an associated fault.

Along the northeast side of Salton Sea, 6,000 feet of incompetent lacustrine beds are upended on the southwest side of the San Andreas fault. They are tilted steeply away from the fault, and are buckled into numerous small, tight folds with axes that trend N. 75° W. as compared to the N. 50° W. bearing of the fault. These obviously are a result of right lateral drag movement on the fault.

Northwestern Imperial Valley

San Jacinto Fault Zone. The San Jacinto fault is parallel to and similar to the San Andreas fault, but is far more complex. It is essentially a zone of discontinuous faults in a belt 4 to 6 miles wide. The faults generally are vertical, and are marked by long, straight scarps that face mostly to the southwest. The main San Jacinto fault is strongly developed at the northeast edge of Borrego Valley, where it forms a high, southwest-facing scarp. Aligned with this fault in areas to the southeast are the Superstition Mountain, Superstition Hills, and Imperial faults, the last-named of which extends southeastward into Mexico.

The Clark, Buck Ridge, and Santa Rosa faults branch off eastward from the San Jacinto fault, and extend through the southwest slope of the Santa Rosa Mountains into Clark Valley. Aligned with these faults to the southeast is the San Felipe Hills fault along the southwest edge of the San Felipe Hills.

The Santa Rosa Mountains and San Felipe Hills were elevated along this group of faults, which are a part of the general San Jacinto fault zone. The major movements on most, if not all, of the northwest-trending faults of the San Jacinto zone are right lateral, and vertical movements are either apparent or local, and commonly are reversed. Physiographic evidence of right lateral movement is present along the San Jacinto, Clark, and Buck Ridge faults north of Borrego Valley, chiefly in the form of offset canyons, and structural evidence is furnished southeastward from Clark Valley by numerous tight, east-trending folds in the Cenozoic strata.

Evidence of recent movements along several faults of the San Jacinto zone is not confined to the occurrence of straight scarps and offset gullies. On the Clark fault east of Clark Lake is a 300-foot, northeast-facing scarp in the alluvium. Recent breaks along the Superstition Hills fault were noted in February 1951 by Joseph Ernst, who reports (oral communication, August 1953): "Recently formed surface fractures developed along 2 miles of the Superstition Hills fault, on which a mild earthquake reported in Imperial Valley on January 29, 1951, probably originated, were from 50 feet to 100 feet long, generally vertical, gaping to ¼ inch. The fractures formed en echelon along the course of the fault, trending N. 20° W. as compared to the N. 50° W. trend of the fault." The severe earthquake of May 18, 1940, in Imperial Valley was caused by a movement on the Imperial fault. Roads, fences, and rows of citrus trees were offset laterally on this fault, with the northeast block displaced relatively southeastward. There was no observable vertical displacement. Horizontal displacement amounted to 3 feet near Imperial, 6 feet east of El Centro, and to as much as 13 feet near Calexico.

Minor vertical, northeast-trending cross faults are present within or near the San Jacinto fault zone in the Borrego Badlands and in the Superstition Hills. Associated with these faults are many tiny, east-trending, tightly squeezed drag folds, which indicate a left lateral drag or relative southwestward displacement of the northwest blocks.

Folding in the Cenozoic Sediments. The structure of the Cenozoic sediments exposed from the Santa Rosa Mountains southeastward through the Superstition Hills is extremely complex. Around the southeastern Santa Rosa Mountains the sediments are arched into the broad Santa Rosa anticline, which plunges southeast. This fold is cancelled out southeastward by the Borrego synclinorium, which plunges westward toward Clark Valley. South of this synclinal structure is the San Felipe anticlinorium, the major axis of which bears east-west through Borrego Mountain and the San Felipe Hills. At Borrego Mountain this anticlinal uplift is cut by the San Jacinto fault and its branches, and diorite is exposed west of the main fault; from this area the fold plunges and veers northwestward toward Borrego Valley. The recency of movement on this structure is indicated by several northeast-trending minor folds developed in the older alluvium across San Felipe Wash west of Borrego Mountain.

East of Borrego Mountain the San Felipe anticlinorium plunges eastward through the San Felipe Hills. The major axis is offset by right lateral movement along the San Jacinto and San Felipe Hills faults. Superimposed on the above-described major folds are innumerable minor, east-trending folds. These are especially abundant along the San Jacinto and San Felipe faults, or in areas where these faults die out southeastward, and obviously are a result of right lateral drag along these major faults.

The Superstition Hills is an anticlinal uplift on the northeast side of the Superstition Hills fault, and the northern part of this uplift is a series of many small, east-trending folds in the Brawley formation. These are developed en echelon adjacent to the minor northeast-trending faults. In the low, flat area between the Superstition Hills and the San Felipe Hills are several additional northeast alignments of tiny, east-trending folds, some of which probably are of relatively recent development.

Southwestern Imperial Valley

Elsinore Fault Zone. The Elsinore fault zone is even more complex than the San Jacinto fault zone. It covers a wider area, involving a strip of low mountains, 8 to 12 miles wide, that includes Granite Mountain, Vallecito-Fish Creek Mountains, Carrizo Valley, and the Coyote Mountains. The Elsinore fault forms the southwest margin of this block, and is the largest individual fault. The Earthquake Valley and San Felipe faults branch off eastward from it, and themselves feather out into many branches.

Granite Mountain and the Vallecito-Fish Creek Mountains are composed of massive plutonic rocks that have been shattered and broken into numerous fault blocks, probably by lateral shear or torsion movement on and between the major faults. The western parts of these mountains were elevated along the Elsinore and Earthquake Valley faults, and the eastern parts along the San Felipe fault system, to form a tectonic shear block. In the Vallecito and Fish Creek Mountains are several northeast-trending, steeply dipping normal faults, most of which show elevation on their northwest sides. The largest of these forms the steep southeast front of the Fish Creek Mountains. These faults probably are a result of northwestward tilting of major blocks of dominantly granitic rocks.

The Coyote Mountain range was elevated along the Elsinore fault and tilted northward. The upended metasediments of this range strike southeast in the Carrizo Mountain portion, thence curve southward and nearly westward into the Elsinore fault. The anomalous westerly trend may have been produced by right lateral drag on the fault. In the western part of the range are many minor faults that trend south of west, parallel to the bedding of the metasediments, and that probably have left lateral offsets.

Vertical displacements along the Elsinore fault are locally great, but probably are more apparent than real, as the distribution of rock types indicates that they are twice reversed. A great amount of right lateral movement is indicated by tight, east-trending drag folds in the Cenozoic sediments on the south side of the Coyote Mountains.

Folding in the Cenozoic Sediments. On the north side of Carrizo Valley the sedimentary rocks dip homoclinally southwest to form the only completely exposed sequence of Cenozoic strata in Imperial Valley. Southward from Carrizo Wash the structure is complex. In the northwestern Coyote Mountains the sediments dip northwest. As this range was elevated along the Elsinore fault on its southwest base, the Tertiary sediments on the south side of the fault are upended and wrinkled into sharp folds that strike into it from the west, indicating right lateral drag. The Imperial and Palm Spring formations, as exposed from the eastern Coyote Mountains southeastward to Signal Mountain, are compressed into many open folds that generally trend and plunge northeastward. The folds are more numerous and complex adjacent to the Laguna Salada fault, where even the older alluvium is locally deformed.

Regional Tectonics

The regional trend of the upturned metamorphic rocks is northwest in the mountains bordering the Imperial Valley region, indicating that prior to invasion of the plutonic rocks, the metamorphic rocks were folded by a great regional northeast-southwest compressive stress.

The complex of basement rocks evidently reacted to late Cenozoic stresses as a comparatively rigid mass, except where it was rendered semi-pliable by shearing along the major fault zones. The overlying sedimentary fill, in contrast, reacted as a pliable cover. The strain pattern in the Imperial Valley region is clearly defined. The primary strain features are the northwest-trending high-angle faults developed along the San Andreas, San Jacinto, and Elsinore zones. Movements along these faults are predominantly right lateral, with relative southeastward displacements of the northeast blocks, and vertical movements are local or only apparent. The secondary or subsidiary strain features are: (1) the northeast-trending minor faults with left lateral movements, probably formed by slight clockwise rotation of northeast-trending blocks that in turn was caused by right lateral drag along the major northwest-trending faults; (2) northeast-trending normal faults; and (3) series of generally east-trending folds developed en echelon in the sedimentary fill along or near the major fault zones. This strain pattern in general is similar to that of the Transverse Range belt of southern California, except that thrust faults are not developed and the upended Cenozoic strata are not overturned.

The primary overall strain in the Imperial Valley region during late Cenozoic time has been torsional in a clockwise direction. The northeastern part of the region has moved southeastward relative to the southwestern part. This strain could result only from a general northwest-southeast clockwise torsional stress.

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