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GEOLOGY AND OIL RESOURCES  
OF THE ELK HILLS  
CALIFORNIA

CANCELLED

INCLUDING NAVAL PETROLEUM RESERVE No. 1

BY

W. P. WOODRING, P. V. ROUNDY  
and H. R. FARNSWORTH



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# GEOLOGY AND OIL RESOURCES OF THE ELK HILLS, CALIFORNIA

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By W. P. WOODRING, P. V. ROUNDY, and H. R. FARNSWORTH

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## INTRODUCTION

### OUTLINE OF HISTORY OF FIELD AND PURPOSE OF REPORT

During the development of the Sunset-Midway oil field, which lies along the southwest edge of San Joaquin Valley, attention was soon drawn to the Elk Hills, as it was apparent to anyone familiar with oil-field development in California that the Elk Hills are geologically similar to the Buena Vista Hills. As the result of field work carried on by the United States Geological Survey in 1908 the Elk Hills were withdrawn from agricultural entry in September of that year, were classified as oil land in June, 1909, and in accordance with the policy then in operation were withdrawn in September, 1909, from all forms of location and entry pending the enactment of suitable legislation for the leasing of oil and gas lands in the public domain. At that time only one shallow well had been drilled in the Elk Hills, and development in the Buena Vista Hills had barely begun. During the period from 1910 to 1912 a number of wells were drilled in the Elk Hills. This prospecting conclusively showed that oil and gas were to be found there at exploitable depths, but the available results were unsatisfactory. Many of the wells were too shallow to serve as adequate tests, and it was difficult to obtain reliable information relating to most of the few wells that yielded oil and gas, as the lands on which they were drilled were under litigation. In September, 1912, Naval Petroleum Reserve No. 1, which embraces almost the entire area of the Elk Hills (see pl. 1), was created by Executive order.

The first commercial production in the Elk Hills was obtained in January, 1919, when the Standard Oil Co. brought in the first well in sec. 36, T. 30 S., R. 23 E., a school section lying almost in the center of the hills, in the area called the central field in this report. This well yielded an average daily production for the first month of about 225 barrels of oil. Later development in this section, based on

recommendations made by the Department of Petroleum and Gas of the California State Mining Bureau, now called the Division of Oil and Gas of the Department of Natural Resources, revealed a rich dry gas zone lying above the oil zone. Early in 1920 the Standard Oil Co. completed several wells, each of which yielded an initial daily production of 4,000 to 8,000 barrels of oil in sec. 36, T. 30 S., R. 24 E., another school section lying near the east end of the hills, outside the boundary of the naval petroleum reserve. The Standard Oil Co. later began drilling in the adjoining section to the east (sec. 31, T. 30 S., R. 25 E.), which was leased from the Kern County Land Co. The Pacific Oil Co., which held land patented to the Southern Pacific Co., started operations in sections adjoining the Standard Oil Co.'s properties, both within the reserve, in sec. 31, T. 30 S., R. 24 E., and outside the reserve, in sections 35 and 25, and later in section 27. At first drilling on the public lands was confined to the east end of the hills, called the eastern field in this report, where the Pan American Petroleum Co. in 1921 and 1922 acquired leases within the boundary of the reserve, in secs. 1, 2, and 3, T. 31 S., R. 24 E., as well as outside the reserve, in sec. 6, T. 31 S., R. 25 E. Other public lands in this field lying outside the reserve, in sec. 26, T. 30 S., R. 24 E., were leased by the Union Oil Co., Associated Oil Co., and Leland Oil Co. In 1922 the Belridge Oil Co. and the Elk Hills Petroleum Co., a subsidiary of the Pan American Petroleum Co., obtained leases in sec. 34, T. 30 S., R. 24 E., within the reserve. Finally the remaining public lands within the reserve were leased to the Pan American Petroleum Co. under the lease known as Naval Reserve No. 10, dated December 11, 1922. The Government brought suit to annul this lease. Under the decree handed down by the United States Supreme Court on February 28, 1927, the lease was annulled, and the lands were restored to the Government and now are under the administration of the Navy Department.

As a result of the developments outlined in the preceding paragraph, the annual production of oil from the Elk Hills rose rapidly from 291,000 barrels in 1919 to 17,990,000 barrels in 1921. The effects of overproduction in the newly discovered fields in the Los Angeles Basin early in 1922 were felt in the Elk Hills as elsewhere. Consequently, late in 1922 and throughout 1923 almost half the potential production was closed in, and the production dropped to 8,087,000 barrels in 1923. Early in 1924 the wells were again yielding almost their full production, and in 1924 the output was 13,530,000 barrels. During the middle of 1925 and again in 1927-28 the production of this field and of others in San Joaquin Valley was curtailed by the shutting in of wells.

The purpose of this report is to describe the geology of the Elk Hills and the occurrence of the oil and gas, to trace the movements of oil, gas, and water in the developed areas, and to discuss

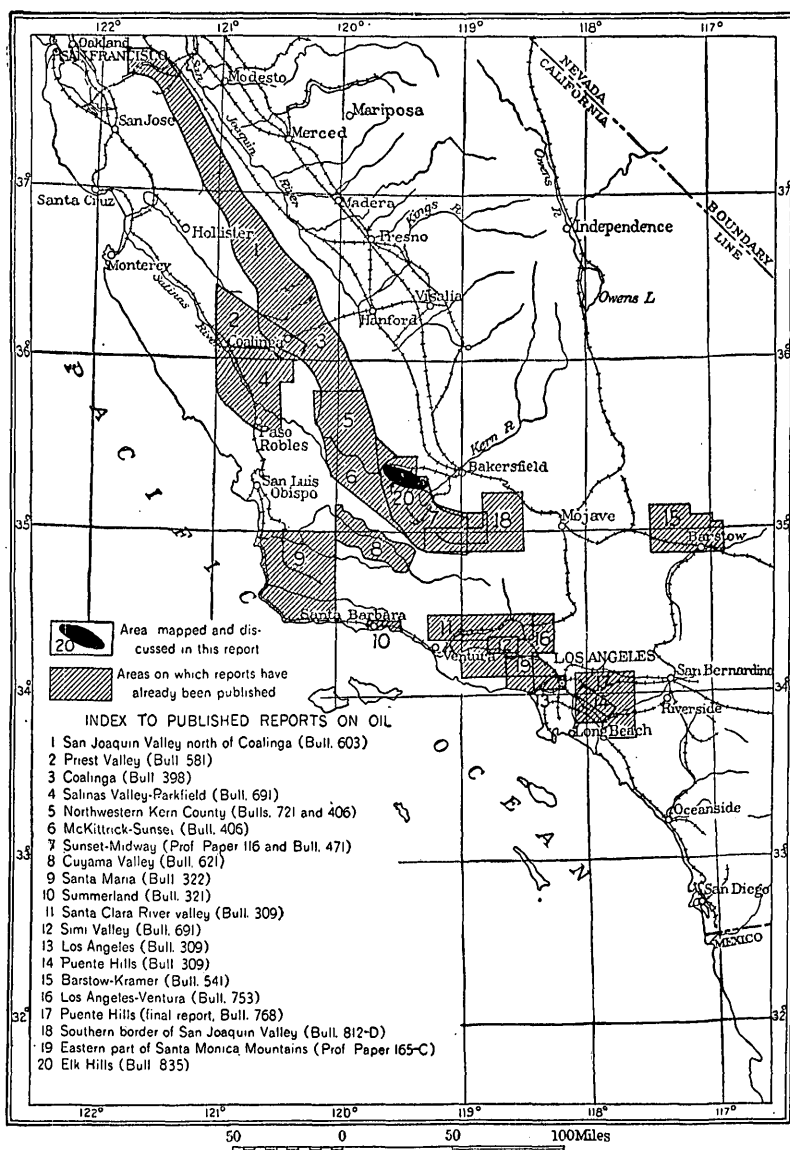


FIGURE 1.—Index map of a part of California, showing areas discussed in oil reports published by the United States Geological Survey

the oil possibilities of the undeveloped parts. The history of the field and its production also are set forth.

#### LOCATION

The location of the Elk Hills with reference to other areas containing oil fields in California is shown in Figure 1. The Elk Hills

lie in southwestern Kern County, in the foothills of the Temblor Range, along the southwest edge of San Joaquin Valley—the southern part of the Great Valley of California. The Temblor Range, which is one of the Coast Ranges, extends southeastward and partly merges into the eastward-trending San Emigdio Mountains, which lie along the south edge of San Joaquin Valley. Foothills along the northeast flank of the Temblor Range, adjoining the valley, form a wedge that increases in width toward the southeast until it attains a maximum width of about 12 miles near the southeast end of the range. Here, at the base of the wedge, the foothills merge into the flat floor of the valley, part of which receives the flood waters of the Kern River in the reservoir called Buena Vista Lake. The Elk Hills lie along the north side of this wedge of foothills, adjoining its base. They are isolated from the foothills to the south by the Buena Vista Valley and its northwestward continuation, the McKittrick Valley, in which lies the town of McKittrick. (See fig. 3.) The foothills south of the Buena Vista Valley, called the Buena Vista Hills, are separated from the Temblor Range by the Midway Valley, in which lie the towns of Taft and Fellows. Taft is the larger of these two towns and supplies the near-by oil fields.

The Sunset-Midway oil field is the largest field in California both in producing acreage and in total production. It embraces part of the northeast flank and southeast end of the Temblor Range, the southeastern part of the Midway Valley, the Buena Vista Hills, and Maricopa Flat—an area along the west edge of San Joaquin Valley where the northern part of the Temblor Range plunges into it. The geology of the Sunset-Midway field and the development of its oil resources up to July, 1916, are described by Pack<sup>1</sup> and Rogers.<sup>2</sup> Pack also gave a description of the Elk Hills, but at the time he wrote only a few wells had been drilled there, and none were producing oil for the market. The Elk Hills field is separated from the Sunset-Midway field by the Buena Vista Valley. The area of production on the north slope of the eastern Buena Vista Hills has recently been extended down into the southern part of the Buena Vista Valley. The old McKittrick field, well known for its complex geologic structure and for long-lived wells that yield a small daily production, lies southwest of the Elk Hills, near McKittrick.

#### FIELD WORK AND ACKNOWLEDGMENTS

The first of the field work on which this report is based was done during two months in the summer of 1924 by Messrs. Woodring and

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<sup>1</sup> Pack, R. W., The Sunset-Midway oil field, Calif., pt. 1, Geology and oil resources: U. S. Geol. Survey Prof. Paper 116, 1920.

<sup>2</sup> Rogers, G. S., The Sunset-Midway oil field, Calif., pt. 2, Geochemical relations of the oil, gas, and water: U. S. Geol. Survey Prof. Paper 117, 1919.

Roundy with the assistance of H. W. Hoots. At that time no topographic map of suitable scale was available, and mapping was carried on by plane-table traverse. Additional work was done during the following year with the assistance of a topographic map, but the map used as a base for Plate 1 was not available until 1928, and at that time the geology of virtually the entire area was remapped by the senior author.

The parts of this report dealing with the surface features and surface geology were written by Mr. Woodring; the part dealing with the underground geology was prepared by the three authors; of the other parts, the discussion of the occurrence of the oil and gas was written by Messrs. Roundy and Farnsworth, of the production by Mr. Roundy, and of the waters and their movements by Mr. Farnsworth.

The oil companies operating in the Elk Hills field cooperated liberally in the preparation of this report by furnishing logs, production, and repair records, and other data bearing on the movement of the waters. For these and other courtesies the authors are greatly indebted to F. H. Hillman, G. C. Gester, J. M. Atwell, E. J. Young, and P. C. McConnell, of the Standard Oil Co.; M. E. Lombardi, E. G. Gaylord, and J. H. Menke, of the former Pacific Oil Co., which has since been consolidated with the Standard Oil Co.; J. C. Anderson, Van H. Manning, F. E. O'Neill, L. P. Brandel, and L. F. Kohle, formerly of the Pan American Petroleum Co., which in 1928 transferred its properties to the Richfield Oil Co.; J. A. Taff, G. D. Hanna, J. B. Stevens, and W. D. Cartright, of the Associated Oil Co.; C. L. Woods and Ted Miles, of the Union Oil Co. of California; L. E. Porter and M. E. Lake, of the Richfield Oil Co.; C. L. Moore, of the Chanslor-Canfield Midway Oil Co.; L. A. Cranson, of the Honolulu Consolidated Oil Co.; F. F. Doyle, of the Midway Gas Co.; and E. Huguenin, H. A. Godde, and E. H. Musser, of the California Division of Oil and Gas. The late Admiral H. H. Rousseau, director of naval oil reserves, Commander I. F. Landis, inspector of naval oil reserves in California, and C. M. Nickerson, resident petroleum engineer of the Navy Department, placed at the authors' disposal the records accumulated during their administration of Naval Petroleum Reserve No. 1. R. C. Patterson and J. M. Alden, of the Taft mineral leasing office, formerly administered by the Bureau of Mines and now under the direction of the Geological Survey, constantly furnished information relating to wells drilled on Government land. The airplane photographs used as illustrations were furnished by the Navy Department.

## EARLIER REPORTS

The following reports deal with the geology and oil resources of the Elk Hills. In addition to the special articles listed, the monthly chapters of the annual report of the California State oil and gas supervisor, issued by the California State Mining Bureau, now called the Division of Oil and Gas of the Department of Natural Resources, under the title "Summary of operations, California oil fields," give a record of drilling and other operations and a biennial summary of production statistics.

1910. Arnold, Ralph, and Johnson, H. R., Preliminary report on the McKittrick-Sunset oil region, Kern and San Luis Obispo Counties, Calif.: U. S. Geol. Survey Bull. 406, 225 pp., 5 pls., 2 figs. The geology and oil prospects of the Elk Hills are discussed on pp. 81, 93, 99-100, 209-210.
1914. McLaughlin, R. P., and Waring, C. A., Petroleum industry of California: California State Min. Bur. Bull. 69, 519 pp., 78 figs., 13 unnumbered plates in text, 18 pls. in atlas. Development in the Elk Hills is briefly described on pp. 218-219, including list of early wells drilled, their location, depth, and results of drilling.
1919. McLaughlin, R. P., Natural gas development in the Elk Hills, Calif.: California State Min. Bur. Summary Operations California Oil Fields, May, 1919, pp. 4-8, 1 fig. Account of the discovery of the gas zone in sec. 36, T. 30 S., R. 23 E.
1920. Pack, R. W., The Sunset-Midway oil field, Calif., Part 1, Geology and oil resources: U. S. Geol. Survey Prof. Paper 116, 179 pp., 45 pls., 15 figs. The geology of the Elk Hills and development are described on pp. 17, 49, 57, 58-59, 162-169.
1921. Collom, R. E., The Elk Hills oil field: California State Min. Bur. Summary Operations California Oil Fields, vol. 7, No. 1, pp. 5-6. Introduction to the 1921 report by Thoms, C. C., and Smith, F. M., listed below.
1921. Thoms, C. C., and Smith, F. M., Notes on Elk Hills oil field: California State Min. Bur. Summary Operations California Oil Fields, vol. 7, No. 1, pp. 7-19, 4 pls., 2 figs. Describes the underground structure, development, and technology.
1921. Vander Leek, Lawrence, Petroleum resources of California with special reference to unproved areas: California State Min. Bur. Bull. 89, 186 pp., 12 figs., 12 pls. (including maps). The Elk Hills field is described on pp. 169-171.
1924. Hanna, G. D., and Gaylord, E. G., Description of a new genus and species of fresh-water gastropod mollusk (*Scalax petrolia*) from the Etchegoin Pliocene of California: California Acad. Sci. Proc., 4th ser., vol. 13, No. 9, pp. 147-149, 2 figs. A description of the peculiar fossils used as guide fossils by the oil operators.
1925. Saunders, L. W., Recent developments in the east end of the Elk Hills oil field: California State Min. Bur. Summary Operations California Oil Fields, vol. 10, No. 11, pp. 5-11, 3 pls. A discussion of the underground structure and development of the eastern field.
1926. Woodring, W. P., Pliocene *Viviparus*-like opercula from California: Nautilus, vol. 39, No. 4, pp. 109-111. A brief account of the fossils described by Hanna and Gaylord, 1924, listed above.



1926. Hanna, G. D., Further notes on *Scalex petrolii*: Nautilus, vol. 40, No. 1, pp. 14-16.
1927. Roberts, D. C., Fossil markers of Midway-Sunset-Elk Hills region in Kern County, Calif.; California State Min. Bur. Summary Operations California Oil Fields, vol. 12, No. 10, pp. 5-10, 4 pls.
1927. Woodring, W. P., and Roundy, P. V., Geology and oil development of the Elk Hills, Calif. [abstract]: Washington Acad. Sci. Jour., vol. 17, No. 10, pp. 271-272.
1929. Pemberton, J. R., Elk Hills, Kern County, Calif.: Structure of typical American oil fields, vol. 2, pp. 44-61, 6 figs. An account of the geology and oil production.

## SURFACE FEATURES

### GENERAL RELATIONS

The Elk Hills are a low elongate swell that is crudely elliptical in outline, having a length from northwest to southeast of about 17 miles and a maximum width of almost 6 miles. They are part of the outer foothills of the Temblor Range but are completely detached from the adjoining foothills and form one low range of hills. Except at places where erosion has modified their edge the hills rise gradually from San Joaquin Valley, which lies to the north and east, and from Buena Vista and McKittrick Valleys, which lie to the south. A narrow stream gap extending across the outer range of foothills at the northwest edge of the area shown on Plate 1 separates the Elk Hills from the much narrower range of foothills that extends northwestward along the foot of the Temblor Range. This gap is used by the railroad from Bakersfield to McKittrick. In the eastern two-thirds of the Elk Hills the main stream divide closely follows the center of the hills, but in the western third it gradually bends toward the south edge. The hills rise to an altitude of 1,551 feet above sea level, or about 1,000 to 1,200 feet above the edge of San Joaquin Valley. At places narrow ridges, which are narrow anticlines, interrupt the slope from the crest of the hills to the lowlands that almost completely surround them.

### EROSION FORMS

The hills are intricately dissected by many-branched ephemeral streams. As the climate is semiarid, and during the greater part of the year the hills support only a sparse vegetation consisting of tufts of dry grass and scattered low shrubs, the dissection stands out in bold relief. The divides are narrow but are not knife-edged, and the slopes between gullies and ravines are smoothly rounded. Contour lines representing these slopes form short, full scallops, which are clearly evident on Plate 1, particularly on most of the north

slope, where erosion is deeper. Even at places where during the summer the ground is almost bare, the slopes and hilltops are smooth and rounded, and the knife-edged summits, sharp pinnacles, and fluted slopes of badlands are absent. The rounded divides, smooth slopes, and complexly branching ephemeral streams are shown in Plate 2.

Although the climate is semiarid, the erosion features are like those of a more humid region. Bryan<sup>3</sup> suggested that the humid aspect of erosion features in foothills of Sacramento Valley, the northward prolongation of San Joaquin Valley, is due to the seasonal distribution of the rainfall and to the relatively high winter temperature. Grass begins to grow when the fall rains begin, and the mild temperature permits continuous and rapid growth during the winter. This protective covering of vegetation retards erosion during the period of heaviest rainfall. The grass dries up in the summer, but as little or no rain falls then, there is very little erosion. Probably the same explanation can be applied to the erosion features of the Elk Hills. The rocks in the Elk Hills consist of loose sand and hardened mud, some beds of which carry layers of marlstone or limestone. The rainfall is less than in Sacramento Valley. Bakersfield, the nearest precipitation station of the Weather Bureau, has a mean annual rainfall of 5.5 inches, and on the west side of San Joaquin Valley, where the Elk Hills lie, the rainfall is even less—between 4 and 5 inches. At Bakersfield a little more than 75 per cent of the rain falls during the period from November to March, inclusive; in the vicinity of the Elk Hills the seasonal distribution of the rain is similar, and the rains usually are gentle. If the rainfall were more uniformly distributed during the year, or if the winter temperatures were lower, thus preventing a vigorous growth of grass when erosion is active, or if the rains usually were torrential, soft rocks like those in the Elk Hills would surely be carved into badlands.

The regularity of the slope is somewhat modified, because the mudstones are harder than the sands between which they lie and form short, relatively steep slopes, whereas the sands generally form long, gentle slopes. At places where thin layers of marlstone or limestone are included in the mudstones this difference in slope is most pronounced. The marlstone or limestone, which usually lies at the top of a bed of mudstone, is harder than the other rocks. Where the beds lie flat or dip gently the limy beds crop out at the top of a steep, terracelike step; a bed of mudstone crops out on the rise; and the long, gentle slope of the tread leading down to the next rise is formed on a bed of sand. These steps are for the most part too low to show

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<sup>3</sup> Bryan, Kirk, *Geology and ground-water resources of Sacramento Valley, Calif.*: U. S. Geol. Survey Water-Supply Paper 495, p. 20, 1923.

on a map with a contour interval of 20 feet. Where the beds dip steeply low *cuestas* are formed. A bed of mudstone generally crops out along the upper edge of the *cuesta* and along the back slope leading down the dip. At places beds of sand that carry heavy courses of gravel also form *cuestas*. Where the dip is only moderately steep, as near the north edge of the central part of the hills, the *cuestas* are poorly defined, but where it is  $15^{\circ}$  or more a series of distinct little *cuestas* is formed. Plate 3 shows such *cuestas* along a small part of an area of steeply dipping beds that extends along almost the entire south edge of the hills.

Another factor has a bearing on the shaping of the surface features. North slopes have a thicker covering of soil than south slopes and support a much heavier growth of vegetation, including at many places even a thick pad of moss. This contrast, which is shown in Plate 7, A, is a striking feature. It has been observed at other places and has been described by Reed as it occurs in the Salinas Valley.<sup>4</sup> The contrast is to be attributed to the shading and consequent retention of moisture on north slopes, which is particularly effective in California, as the rain falls during the winter, when the sun is farthest south. As a result of the heavier protective cover of vegetation, north slopes are smoother and less scarred by gullies. Rock exposures are far better on south slopes, and the difference is so pronounced that in carrying on mapping it is advisable to plan to work northward, with the south slopes in full view. Perhaps this condition is responsible for the deceptive appearance of some of the narrow little anticlines, all of which seem to have steeper dips on the north limb, owing to the development there of prominent dip slopes, whereas on some of the anticlines the south limb is actually steeper, but on that limb the surface cuts across the steeply dipping beds.

The slopes at the edge of the hills have been changed by sedimentation and erosion. Rock waste brought from the hills has been deposited along the north and south edges where streams enter San Joaquin Valley and Buena Vista Valley. As a result of the deposition of this material the hills merge gradually into the lowlands, even where high, narrow anticlines extend along their edge. Relatively steep slopes along part of the west edge of the hills are due to erosion along the stream gap that forms the western boundary of the Elk Hills. The most striking result of erosion along the border of the hills is seen along the northern part of the east edge, where the hills end in steep bluffs. Here the beds dip very gently toward the valley, but the bluffs, which are 30 to 80 feet high, have slopes of  $30^{\circ}$  to  $50^{\circ}$ . They are clearly due to cutting back by stream

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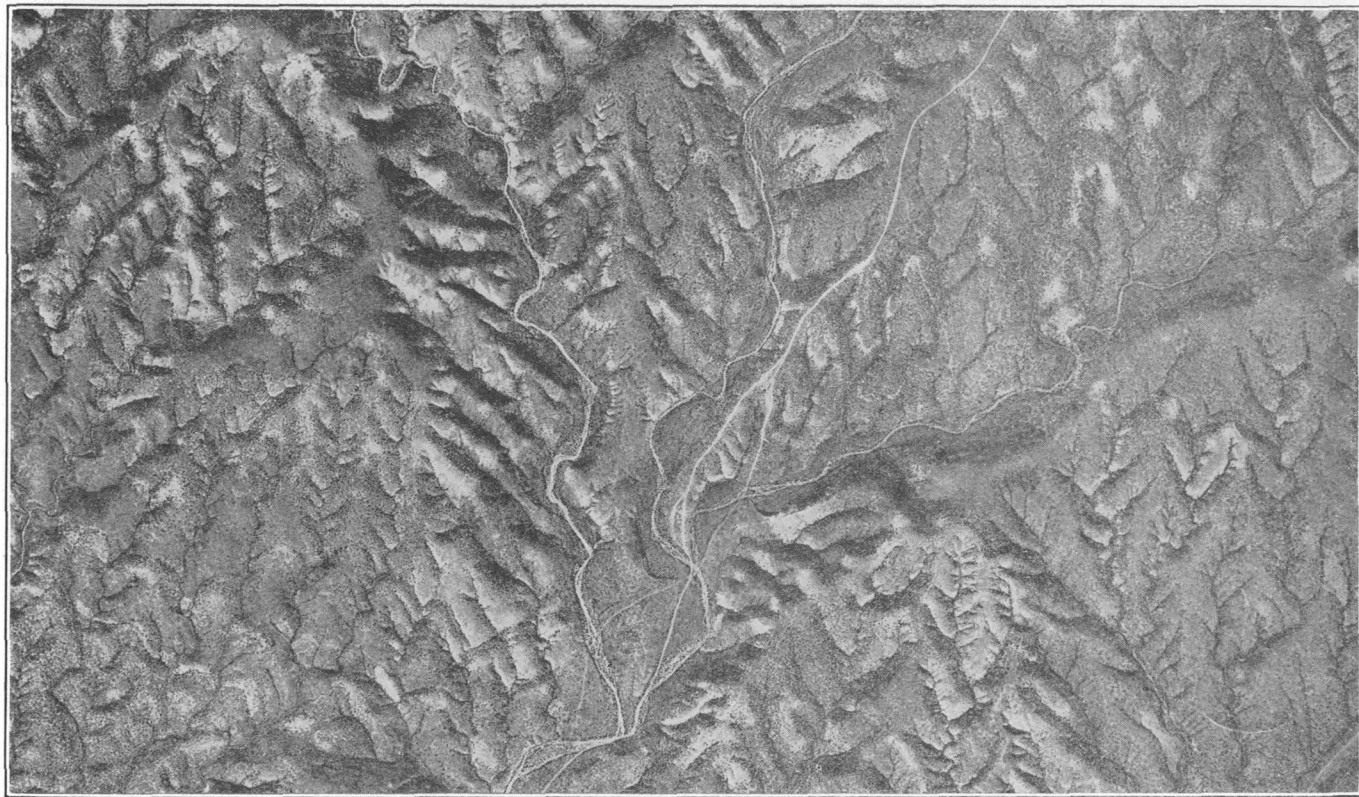
<sup>4</sup> Reed, R. D., Wind and soil in the Gabllan Mesa: Jour. Geology, vol. 35, pp. 84-88, 1 fig., 1927.

erosion. These bluffs extend from the pumping station in sec. 25, T. 30 S., R. 24 E., southeastward along the edge of the hills to a locality about three-quarters of a mile southeast of the Western Water Co. camp. They are not continuous, as they are interrupted by stream channels. The bluffs were cut very recently, at a time when, as at present, the west side of San Joaquin Valley lay in the lee of the Coast Ranges and was as arid as it now is. Therefore it is inferred that the stream that cut them was fed from the Sierra Nevada and flowed in the channel at the east end of the hills now called Buena Vista Slough. The Kern River has built a long, gently sloping alluvial fan extending from the foothills of the Sierra Nevada across San Joaquin Valley to the edge of the Elk Hills, thus shutting off the drainage of the south end of the valley. Before irrigation projects changed the natural drainage, channels of the Kern River radiated across the fan. According to Grunsky,<sup>5</sup> the present main channel, which extends toward the east end of the Elk Hills, where the bluffs are, was formed during floods in 1867-68. Contour lines drawn on the surface of the alluvial fan bulge toward the Elk Hills, showing that earlier channels, of which there is no historical record, extended to the edge of the hills. Flood waters reaching the edge of the Elk Hills through these channels were probably diverted at times southward toward the depression now occupied by Buena Vista Lake and at times northward toward the basin formerly occupied by Tulare Lake. The bluffs were formed by flood waters cutting back the edge of the hills. Active erosion had stopped before the first settlers entered the valley, and the main channel of the Kern River then led southward past the site of Bakersfield to Kern Lake, which has since been drained. Only a relatively small amount of water now reaches the west side of the valley, as canals on the east side have a prior right to a fixed amount. The part of Buena Vista Slough lying near the Elk Hills has been straightened to serve as a canal. Meanders that were cut off when it was straightened, as well as several generations of naturally abandoned meanders, are visible on Plate 4. Some of the artificially abandoned meanders lie along the foot of the abandoned bluffs.

Opposite the village of Tupman Buena Vista Slough retreats from the edge of the hills and the abandoned bluffs end. The edge of the hills recedes southwestward, but the boundary is indefinite because of the cover of rock waste deposited by streams emerging from the hills. The streams are now eroding this old alluvium. The outer boundary of the old eroded alluvium extends along the edge of a terrace adjoining the valley of the stream that formerly

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<sup>5</sup> Grunsky, C. E., *Irrigation near Bakersfield, Calif.*: U. S. Geol. Survey Water-Supply Paper 17, p. 37, 1898.



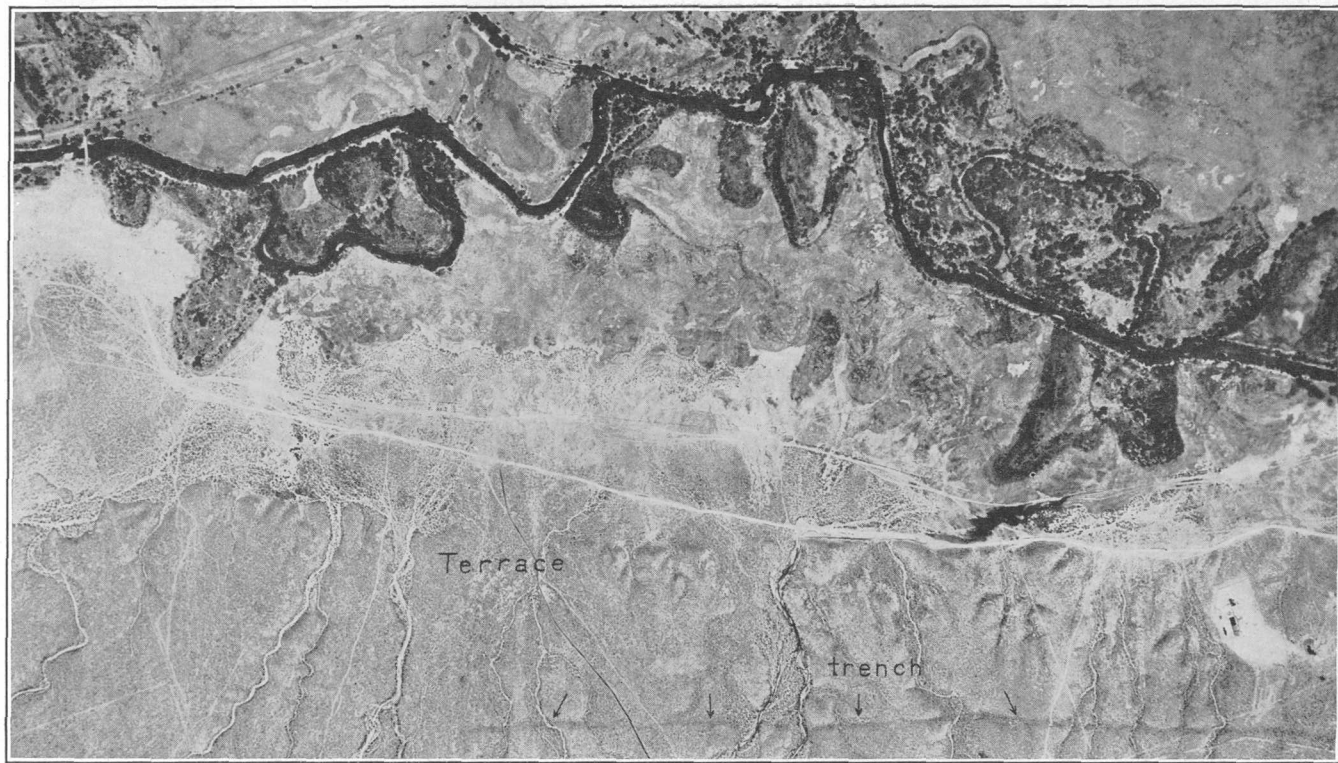
ROUNDED DIVIDES, SMOOTH SLOPES, AND MANY-BRANCHED EPHEMERAL STREAMS CHARACTERISTIC OF THE ELK HILLS  
Airplane photograph of western part of sec. 3, T. 31 S., R. 23 E., on the south slope of the Elk Hills. Approximate scale, 1,100 feet to the inch. The narrow white streak in the right center is an unimproved road. The area at the upper right is slightly dissected. Narrow light-colored scalloped bands, due to steeply dipping beds of mudstone, are visible extending obliquely across the lower left corner.



## LITTLE CUESTAS AT SOUTH EDGE OF ELK HILLS

Airplane photograph of parts of secs. 13 and 14, T. 31 S., R. 24 E. Approximate scale, 1,100 feet to the inch. The black streak at the bottom is the highway from Taft to Bakersfield, from which at the right the Tupman road, a broad black band, branches off. The cuestas are due to beds that dip steeply southward. The rough hills at the left are the result of the erosion of a narrow anticline that plunges eastward and disappears at the left center. Steeply dipping beds on the south limb of a smaller and more deeply eroded anticline are visible at the upper right.





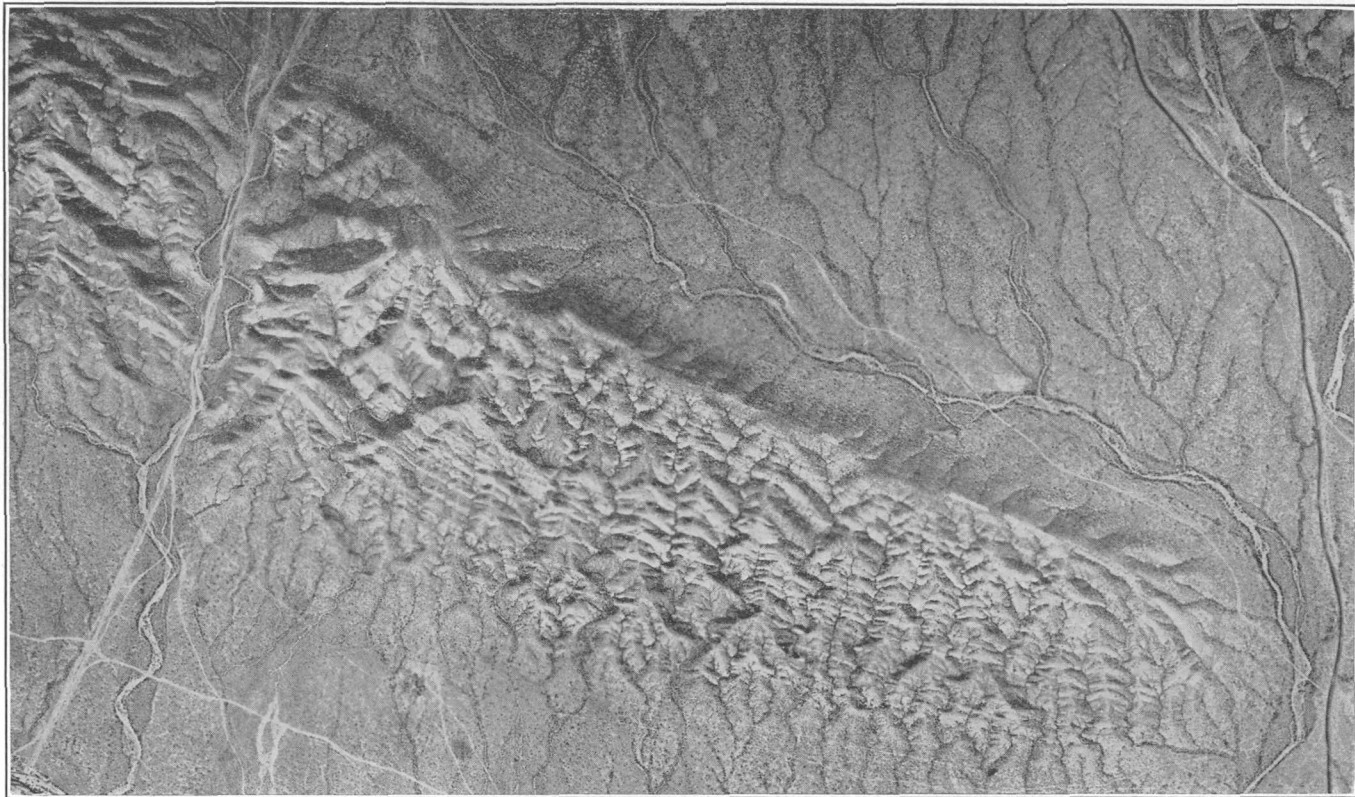
## TERRACE AND TRENCH ALONG NORTH EDGE OF ELK HILLS

Airplane photograph of part of secs. 23 and 24, T. 30 S., R. 24 E. Approximate scale, 1,200 feet to the inch. The streams are eroding the old alluvium that lies on the terrace and are depositing alluvium beyond the edge of the terrace. The trench is the easternmost one along the north edge of the hills. The black sinuous band is Buena Vista Slough. The relative age of the abandoned meanders is suggested by differences in the sharpness of outline.



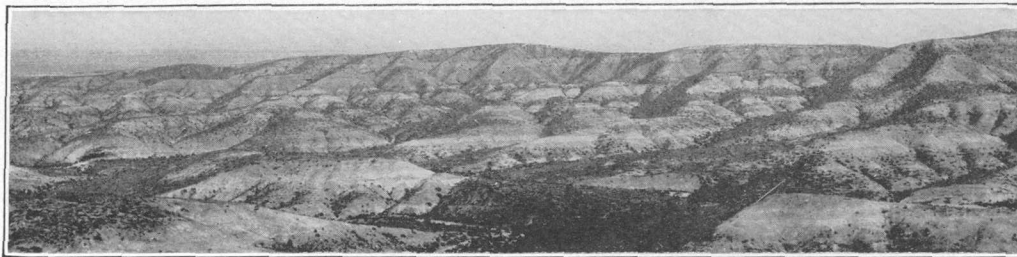
DRAINAGE FEATURES OF WESTERN PART OF NARROW ANTICLINE ALONG SOUTH EDGE OF ELK HILLS WEST OF CARMAN ROAD  
Airplane photograph of parts of secs. 3 and 10, T. 31 S., R. 23 E. Approximate scale 1,100 feet to the inch. The plunging west end of the anticline is roofed by a bed of sand underlying a bed of mudstone, which appears as a white band cropping out on the south limb,





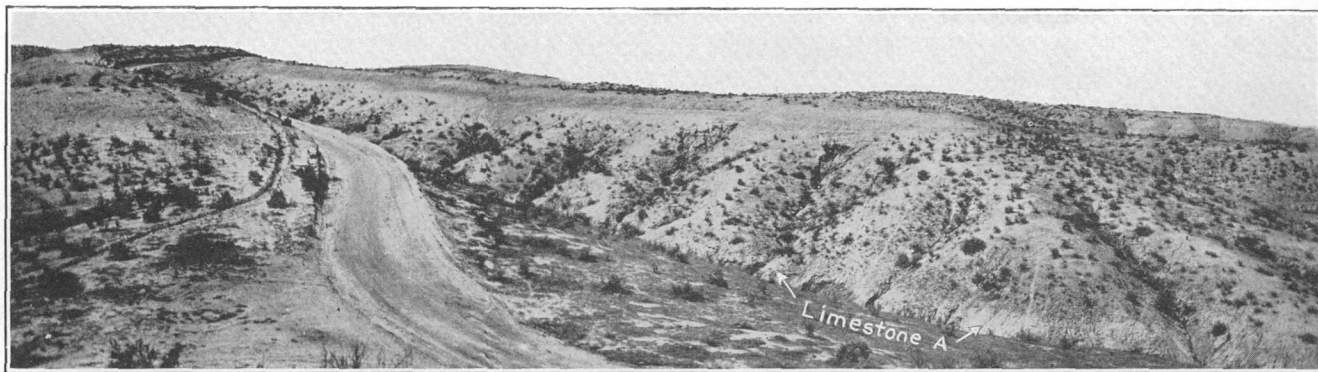
DRAINAGE FEATURES OF EASTERN PART OF ANTICLINE SHOWN IN PLATE 5

Airplane photograph of part of secs. 11 and 12, T. 31 S., R. 23 E. Approximate scale 1,100 feet to the inch. Headward erosion across the crest of the anticline is shown by the numerous southward-draining ravines and gullies. The black streak at the right is the Carman road. The unimproved road through the stream gap follows a pipe line.



A. VIEW ON NORTH SLOPE, LOOKING EASTWARD ACROSS STREAM VALLEY IN WESTERN PART OF SEC. 22, T. 30 S., R. 23 E.

Note the gentle northward dip, the alternating beds of mudstone and sand that show as light and dark bands, respectively, and the heavier growth of vegetation on north slopes.



B. VIEW LOOKING NORTHEASTWARD FROM CREST ROAD IN NORTHWEST PART OF SEC. 3, T. 31 S., R. 24 E.

The mudstone forming the light bare band at the top of the ridge is the third mudstone above the base of the upper part of the Tulare formation. This is the type locality of limestone A, which lies at the top of the second mudstone. A bed of sand covered with vegetation lies between the mudstones.

### TULARE FORMATION IN ELK HILLS

flowed in Buena Vista Slough, where the streams from the hills are now depositing alluvium. At places the outer edge of this terrace is indefinite, but at other places it forms a distinct scarp that rises 15 to 25 feet above the valley. Plate 4 shows the outer edge of this terrace extending westward from the village of Tupman. If this terrace were the result of a general movement of the earth's crust a similar terrace should be found along Buena Vista Creek, south of the Elk Hills, and unless the terrace were formed before the bluffs were eroded, which is not probable, the movement should be recorded by a bench in the bluffs. As no terrace is visible along Buena Vista Creek and as the bluffs are not benched, the terrace seems to have no tectonic significance. It might be due to a change in climate or to a change in direction of drainage that increased the flow of the stream in the channel of Buena Vista Slough. But the bluffs and terrace were formed so recently, after the long alluvial fan of the Kern River was built, that a climatic change seems improbable, and no other evidence supports the supposition that a great volume of water from the Kern River was diverted into Buena Vista Slough during the time when the terrace was cut. It is more probable that the terrace is due simply to the southward migration of the stream that formerly flowed in Buena Vista Slough and to the cutting back of the old alluvium deposited by streams emerging from the hills.

Airplane photographs reveal narrow, shallow trenches at the west end of the hills and along the north edge. As shown on Plate 1, these trenches extend along almost the entire north edge of the hills on each side of the indefinite boundary between the alluvium and the Tulare formation, but at the west end they extend southwestward into the hills. Toward the east end they seem to terminate at faults. The easternmost one, which lies southwest of the village of Tupman, can be seen on Plate 4. The longest virtually continuous trench has a length of a little more than 4 miles. As seen on the ground, they seem to be narrow stream swales, which, however, extend across divides. They are only a few feet deep and 10 to 15 feet wide; in fact, they are so shallow that they were entirely overlooked until their alinement was discovered on the photographs. Inasmuch as they branch and have an irregular rambling trend they can hardly be the remnants of artificial trenches. They resemble rift features on a minute scale, as Pemberton<sup>6</sup> has suggested, but so far as could be determined no displacement has taken place along them. If there is no displacement, the trenches are remnants of

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<sup>6</sup> Pemberton, J. R., Elk Hills, Kern County, Calif.: Structure of typical American oil fields, vol. 2, p. 51, 1929.

open partings or cracks. Such cracks might be due to settling along the edge of San Joaquin Valley, but this view would not account for the trend of the trenches into the hills at the west end. They also might be due to earthquakes; indeed, if they were still open they would closely resemble the cracks that were formed during the San Francisco earthquake of 1906. As described by Gilbert and Lawson,<sup>7</sup> secondary cracks—that is, cracks that were not directly due to the rupture that caused the earthquake—generally were associated with landslides or with lurching toward stream banks, but others apparently were the result of rupturing of the rock by the intense vibrations. Such cracks were formed many miles from the San Andreas rift. If the trenches in the Elk Hills are remnants of earthquake cracks, they fall in the last class. Also, if they formed as earthquake cracks they were open cracks long ago, for they are almost obliterated and they are in the same stage of obliteration. The closest fault along which movements are known to have taken place recently is the San Andreas rift, which lies 16 to 17 miles to the southwest. A severe shock, called the Fort Tejon earthquake, was caused by movements along this fault in 1857. In the event that this shock was the one responsible for the almost obliterated cracks in the Elk Hills, other cracks in the same stage of decay should be found between the Elk Hills and the rift. So far as known they have not been found, but it probably would be necessary to look for them on airplane photographs.

#### DRAINAGE

Inasmuch as folding has taken place so recently in this area, where the surface rocks are of early Pleistocene or late Pliocene age, it is natural to expect that the drainage pattern should conform to the structural features. There are so many exceptions, however, that the conclusion seems inevitable that the history of the drainage pattern is more complex than might at first be supposed, though the evidence collected is too meager to make it possible to trace this history.

The stream draining McKittrick Valley cuts across the entire outer range of foothills in the gap at the west end of the Elk Hills, and branches of Buena Vista Creek cut across the Buena Vista Hills. In the Elk Hills themselves the drainage conforms to the larger folds, but streams cut across the narrow little anticlines. Along several of the larger streams that drain the north slope remnants of old stream deposits that unconformably overlie the surface rocks and that are trenched by the present streams were seen here and

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<sup>7</sup> Lawson, A. C., and others, Report of the State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, vol. 1, pp. 73-76, 401-402, 1908.

there, but these old deposits have been almost entirely cleaned out. No stream deposits were seen anywhere along the crest of the hills, but the slightly eroded area lying in the central part of the hills in the saddle between the two main anticlines has the appearance of a former erosion surface that has so far escaped gullying by headward erosion of the present streams. This area is drained by shallow swales that change within a short distance, though not very abruptly, to deeply trenched gullies. The long, gentle slope leading down the north side of the hills farther west has the same appearance.

The amount of material removed by erosion from the crest of the hills is considerable but rather difficult to estimate. In the eastern part, which is more deeply eroded, a thickness of at least 60 to 80 feet, probably a great deal more, has been removed. Apparently most of this material was carried away by streams, though the close packing of pebbles strewn on the surface of a bed of sand in exposed places, such as the flat crests of the slightly eroded narrow anticlines, shows that the wind can not be ignored as an eroding agent.

The remnants of old stream deposits, the apparent remnants of former erosion surfaces, and the amount of erosion on the crest of the hills point to the conclusion that the hills have grown repeatedly and that more than once they have been eroded down to a level below their present height. The last upward bulge must have been of very recent date; otherwise, despite the aridity, no hills of any magnitude would be left.

The streams that cut across the little anticlines offer an interesting field of study. These anticlines are eroded to varying depths, but even those that are least eroded have had a considerable thickness of beds removed from their crest, and after allowance has been made for the apparently slight amount of wind erosion it is not at all certain that the present streams have done all this work. Some of the streams crossing the little anticlines, particularly those with large drainage basins, may be original antecedent streams that kept their grade across the folds as they bulged upward. Others probably owe their courses to headward erosion, which enabled them to capture drainage lying back of the anticline.

The drainage features of the anticline along the south edge of the hills west of the Carman road seem to afford evidence of breaching by headward erosion. This anticline has not been deeply eroded, and its form is faithfully indicated by the topography, as shown in Plates 5 and 6. The southward-draining gullies are being cut back much more rapidly than the northward-draining gullies, owing to their steeper gradient. Near its west end the anticline is roofed by a bed of sand, though it is clear that this is not the original roof, for higher beds crop out on the south limb. One southward-draining

gully has already been cut headward beyond the crest in this bed of sand. Of the three streams flowing across the part of the anticline shown in Plate 5 the middle one seems to represent a later stage in this process of piercing the anticline by headward erosion, as it flows across the anticline in a very narrow gap and is draining a small area lying north of the anticline. Southeastward-flowing tributaries of this stream have already excavated an amphitheater along the crest of the fold, revealing beds that underlie the sand which forms the roof of the anticline farther west. The larger stream at the right, which has a wider gap and drains a large area to the north, may represent an earlier breach across the anticline, perhaps during an earlier stage of erosion. The still larger stream to the left seems to be an original antecedent stream, as an early breach across this part of the fold, where it is plunging rapidly, is improbable. The stream that crosses the eastern part of the same anticline (see pl. 6) seems to flow in a breach cut during an earlier stage. The stream that flows southeastward along the north edge of this anticline and around its plunging end (see pl. 6) may represent the former outlet of most of the drainage of the area north of the anticline after it had been diverted by the first growth of the anticline. Most of the area lying between the anticline and the crest of the hills, except the part drained by the supposed antecedent stream at the west end, is not deeply trenched, although the stream pattern is intricate. The erosion of this area, which lies in the lee of the anticline, may have been retarded during the period between the diversion of the drainage and the breaching of the fold.

The narrow anticline at the northwest edge of the hills is in an even earlier stage of topographic development. It seems probable that the streams flowing across it have breached the fold by headward erosion and captured part of the drainage of the stream that flows in the trough of the northwestward-plunging syncline south of the anticline. The other narrow anticlines, all of which are pierced by streams, have a much less definite topographic form, and the history of the streams that cross them is not clear.

#### GENERAL STRATIGRAPHY

Nonmarine deposits of early Pleistocene or late Pliocene age, called the Tulare formation, are the only beds that crop out in the Elk Hills. A fringe of Quaternary alluvium extends around the edge of the hills. The Pliocene oil-bearing Etchegoin formation underlies the Tulare formation. Deposits in the upper part of the Etchegoin formation were laid down in marine, brackish, and fresh waters, but the lower part consists entirely of marine deposits. In the Elk Hills the Etchegoin formation is known only from material

brought to the surface by the drilling of wells. In the near-by mountains light-colored siliceous shale and diatomite of great thickness unconformably underlies the Etchegoin formation. This shale, called the Maricopa shale, is of middle and upper Miocene age and is usually regarded as the source of the oil in the Elk Hills and adjoining fields. Other sedimentary rocks of lower Miocene, Oligocene, and Eocene age resting on a basement of metamorphic or igneous Mesozoic rocks probably underlie the Maricopa shale in the Elk Hills.

## QUATERNARY DEPOSITS

### ALLUVIUM

Except at the east end of the Elk Hills, where the Kern River has brought finely divided and weathered rock *débris* from the Sierra Nevada, the alluvium surrounding the hills is derived from beds that crop out in the hills themselves or from the deposits in the Temblor Range that yielded the materials from which the beds of the Elk Hills were formed. The alluvium consists of poorly sorted or unsorted pebbles, sand, silt, and clay. The most common pebbles are small flat pieces of white siliceous shale that have imperfectly rounded ends. At the east end of the hills and at places at the west end stream erosion has produced a sharply defined boundary between the beds that crop out in the hills and the alluvium. Elsewhere the boundary is very indefinite, as the alluvium is virtually indistinguishable from the older beds. It is shown in Plate 1 at the change in slope along the border zone between the hills and the lowlands.

The alluvium unconformably overlies the older beds, successively younger deposits overlapping older deposits and extending farther up the slope of the hills. At places recently deposited alluvium rests on the eroded surface of old alluvium. The varying thickness of beds along the edge of the hills shows that the overlap of alluvium conceals a considerable thickness of tilted deposits. At places where the Tulare beds dip gently along the edge of the hills the dip of the alluvium closely conforms to their dip. At other places where the beds in the hills dip steeply, stream cuts near the edge of the hills may reveal gently dipping alluvium resting on steeply dipping beds. The alluvium is of Quaternary age, but what part of Quaternary time it represents is not known, except that it is apparently younger than early Pleistocene. Along the north edge of the hills the alluvium may be divided into an old part, which is now being eroded, and a new part, which is now being deposited. The old alluvium extends from the edge of the hills to the outer edge of the terrace described in connection with other erosion forms on pages 10-11. It is not known whether these two parts could be recognized elsewhere around the edge of the hills where there is no terrace.

## QUATERNARY OR TERTIARY DEPOSITS

## TULARE FORMATION

## DISTRIBUTION

The Tulare formation crops out over the entire area of the Elk Hills. It has also been mapped in the foothills and on the east slope of the Temblor Range in the near-by Sunset-Midway and McKittrick fields and at intervals southeastward along the foot of the San Emigdio Mountains and northwestward along the foot of the Temblor and Diablo Ranges.

## NAME

Folded nonmarine deposits that conformably overlie the Etchegoin formation in the Kettleman Hills, an isolated anticlinal range of foothills southeast of Coalinga, were called the Tulare formation by F. M. Anderson in 1905.<sup>8</sup> These deposits can not be traced continuously from the Coalinga region to the south end of San Joaquin Valley, and it is improbable that the deposition of nonmarine beds began at the same time in the two regions. The finding of fresh-water beds within the Etchegoin formation<sup>9</sup> and of marine or brackish-water beds 2,500 feet above the base of the Tulare formation,<sup>10</sup> both in the type region of the Tulare formation, indicates that slight changes excluded or admitted marine waters there. Similar conditions in the Midway district during late Etchegoin time are indicated by the discovery of vertebrate remains in the McLeod No. 14 well of the Union Oil Co. in sec. 34, T. 31 S., R. 23 E., in the Midway Valley, at a horizon about 150 feet above the top of the B oil zone as defined by Pack.<sup>11</sup> According to an oral communication from Dr. Chester Stock, of the California Institute of Technology, these remains represent a metapodial of a carnivore and a fragment of a rodent or bird.

In various reports of the Geological Survey these nonmarine beds along the west and south sides of the San Joaquin Valley have been called Paso Robles formation, a name first used by Fairbanks.<sup>12</sup>

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<sup>8</sup> Anderson, F. M., A stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 3d ser., vol. 2, pp. 181-182, 1905.

<sup>9</sup> Arnold, Ralph, Paleontology of the Coalinga district, Fresno and Kings Counties, Calif.: U. S. Geol. Survey Bull. 396, pp. 43-44, 1909. Arnold, Ralph, and Anderson, Robert, Geology and oil resources of the Coalinga district, Calif.: U. S. Geol. Survey Bull. 398, p. 138, 1910.

<sup>10</sup> Arnold, Ralph, op. cit., pp. 46-48, 1909. Arnold, Ralph, and Anderson, Robert, op. cit., pp. 141, 147, 153-154, 1910.

<sup>11</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 88-162, 1920.

<sup>12</sup> Fairbanks, H. W., Geology of a portion of the southern Coast Ranges: Jour. Geology, vol. 6, pp. 551-576, 1898 (see p. 545). See also Hamlin, Homer, Water resources of Salinas Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 89, 1904; Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (No. 101), 1904.



The type locality of the Paso Robles formation is in the vicinity of the town of Paso Robles, in the upper Salinas Valley, which lies in the Coast Ranges west of San Joaquin Valley. According to Anderson,<sup>13</sup> the lower part of the Paso Robles formation at its type locality includes marine beds that are equivalent to the upper part of the Etchegoin formation of the Coalinga region. Inasmuch as at least part of the Paso Robles formation seems to be older than the Tulare formation, and inasmuch as the names were applied to deposits in different basins, the deposits in the Elk Hills are in this report described as the Tulare formation. In a report that was issued after this account was written Hoots<sup>14</sup> assigned to the Tulare formation deposits at the extreme south end of San Joaquin Valley.

#### LITHOLOGY AND THICKNESS

##### EXPOSED BEDS

##### GENERAL LITHOLOGY

The Tulare formation consists of nonmarine deposits laid down under varying conditions. Beds of sand and mudstone similar to those in near-by regions crop out in the Elk Hills. The beds change along the strike, and their thickness varies from place to place. The general lithology and the thickness of the exposed part of the Tulare formation are shown in Figure 2.

The division of the exposed beds into an upper and lower part is based on the color of the mudstones. In the upper part the mudstones are buff; in the lower part they are olive-gray. The color contrast is striking, but it is clear that the change in color takes place at different levels, owing to the lensing out of beds.

The maximum thickness of outcropping beds is at least 700 feet and may be as much as 850 feet. The total thickness of the formation is discussed in the description of the concealed beds. (See p. 25.)

##### UPPER PART

*Stratigraphy.*—The upper part of the Tulare formation consists of alternating beds of sand and hardened mud. (See pl. 7, A.) The lowest buff mudstone in the eastern part of the hills was mapped as the base of the upper part. So far as could be determined this bed is continuous over the eastern third of the hills, at least along the crest and north slope, where it is well exposed. In the western part of sec. 5, T. 31 S., R. 24 E., and in section 6 this bed is not so

<sup>13</sup> Arnold, Ralph, op. cit., p. 47. Arnold, Ralph, and Anderson, Robert, op. cit., p. 142.

<sup>14</sup> Hoots, H. W., Geology and oil resources along the southern border of San Joaquin Valley, Calif.: U. S. Geol. Survey Bull. 812, pp. 286-289, 1930.

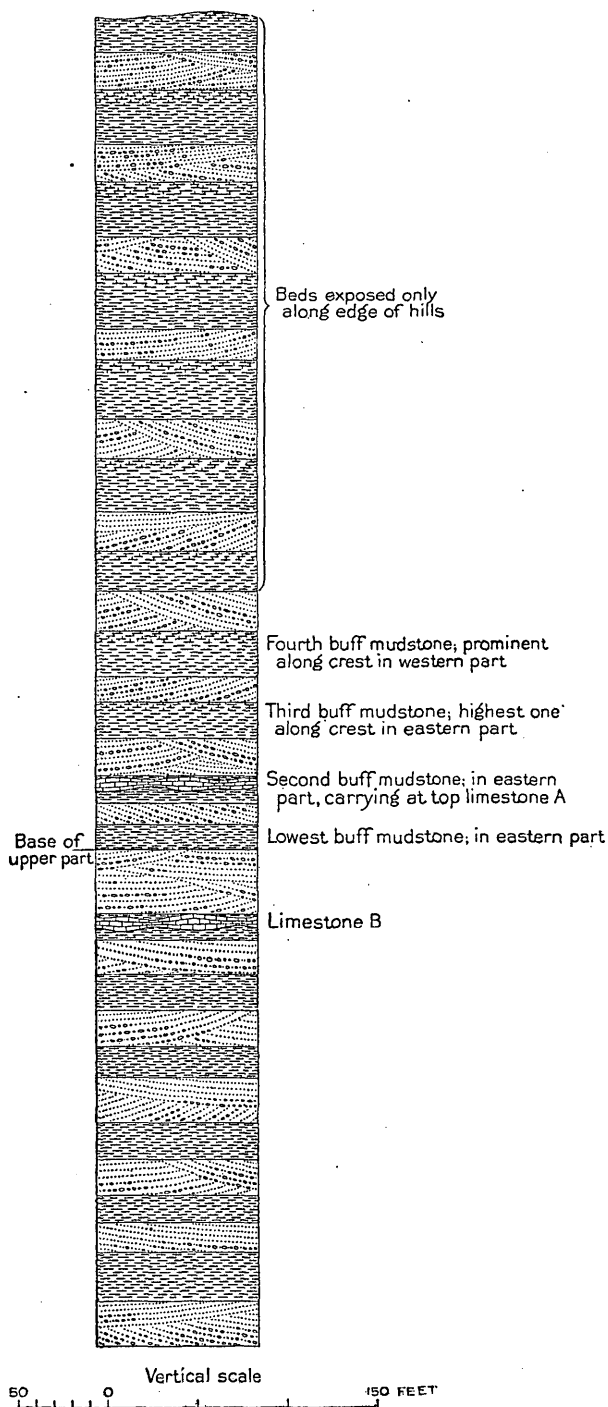


FIGURE 2.—Generalized section of Tulare formation as exposed in Elk Hills

prominent, and in part of this area the lowest buff bed lies at a lower level. Farther west the lowest buff mudstone lies higher in the section, owing to lensing and to a change in color, apparently at this horizon. The lensing out is clearly shown in sec. 24, T. 30 S., R. 23 E., and adjoining parts of the north slope. East of section 24 the lowest buff mudstone over a distance of several miles lies 40 to 50 feet above the bed designated limestone B, which is at the top of the uppermost mudstone in the lower part of the Tulare formation. (See pl. 1.) On the east slope of the high ridge in the middle of section 24, however, this bed lenses into sand, and the first buff mudstone above limestone B lies about 40 feet higher. Farther west on the ridge in section 24 this bed in turn disappears, and a search for a satisfactory mudstone to map as the base of the upper part leads higher and higher in the section to a bed 125 feet above limestone B. In the western third of the hills a grayish mudstone lying 60 to 80 feet below the lowest prominent buff bed was mapped as the base of the upper part in an attempt to maintain essentially the same stratigraphic level as farther east, for, according to the position of limestone B near by, the change in color seems to take place higher in the section.

In the eastern part of the hills the second buff mudstone above the base of the upper part carries at its top a bed designated limestone A, which was used as a datum bed for drawing the structure contours. This limestone is well exposed in the western part of sec. 3, T. 31 S., R. 24 E. (see pl. 7, *B*), which is taken as its type locality. As shown on Plate 1, it was mapped westward along the crest and down the south slope. It also crops out as the higher one of two limestones on the narrow little anticline along the south edge of the hills west of the Carman road. In the second stream gap from the west end of this anticline it consists of two beds of limestone separated by an interval of 5 feet of mudstone. It probably is this limestone that forms long bare dip slopes on the south limb of the Barnodon anticline along the north edge of Buena Vista Hills, on the other side of Buena Vista Valley, where its thickness is as much as 5 feet. This bed lies in the zone of calcareous beds on the north slope of the Buena Vista Hills described and mapped by Pack.<sup>15</sup> Along the crest of the Elk Hills limestone A was not found farther east than the western part of sec. 3, T. 31 S., R. 24 E., though the mudstone that carries it was mapped, and in the northern part of sec. 31, T. 30 S., R. 25 E., on the north slope, a thin limestone was found at this horizon over a small area. This mudstone forms conspicuous out-

<sup>15</sup> Pack, R. W., The Sunset-Midway oil field, Calif., pt. 1, Geology and oil resources:

crops on several tonguelike ridges in the southeast corner of sec. 6, T. 31 S., R. 25 E.

The third buff mudstone above the base of the upper part of the Tulare formation lies 25 or 30 feet above limestone A and is the highest buff bed along the crest in the eastern part of the hills. Where limestone A crops out this bed can readily be recognized as the next overlying mudstone. It is well exposed on the first ridge north of the crest road in the northwest corner of sec. 3, T. 31 S., R. 24 E., where for a short distance it dips 4° or 5° SE., toward a fault. (See pl. 7, *B*.) In this area the overlying sand is the highest bed along the crest of the hills. Farther east the mudstone itself caps the highest hills, and at the east end it apparently has been eroded off.

In sec. 31, T. 30 S., R. 24 E., and farther west along the crest a still higher mudstone, the fourth one above the base of the upper part of the formation, crops out. Its base lies 50 or 55 feet above limestone A. The sand overlying this bed forms much of the surface of sec. 36, T. 30 S., R. 23 E., and adjoining sections to the south and west. The same bed or one lying at about the same horizon—the outcrops are not continuous—is the highest thick mudstone in the western third of the hills, and the overlying sand is generally the highest bed along the crest, though here and there a thin mudstone lies in this sand.

It is apparent from the preceding paragraphs that the thickness of the upper part of the Tulare formation remaining along the crest of the hills increases westward. In the eastern part the maximum thickness is only between 90 and 100 feet, whereas in the western part it is about 150 feet. Beds higher than any along the crest, representing a total thickness of about 450 feet for the upper part of the formation, crop out along the edge of the hills, the thickest section being found along the south edge of the eastern part, where a stadia traverse in secs. 9 and 16, T. 31 S., R. 24 E., gave a thickness of 465 feet for the upper part. These beds, like those along the crest, consist of alternating sands and buff mudstones.

*Lithology.*—The hardened muds are the most conspicuous beds in the upper part of the Tulare formation. These beds are massive and range in thickness from 10 to 40 feet, but most of them are 20 to 25 feet thick. They have a rather uniform light-buff color (17' *f* of Ridgway's "Color standards"). When moistened the mud swells, and when wet it is very plastic. Weathered surfaces slack and crumble and are covered with a thick coat of powdery dust, especially on gentle slopes, but in excavations and stream cuts the mud is firm and hard. Therefore the term mudstone is used for this rock. The weathered, almost bare slopes, where the beds are usually seen, give an erroneous impression of soft material. The mudstones are harder

than the sands between which they lie and form steeper slopes. Except on north slopes, they support only a sparse growth of vegetation or are quite barren, in contrast with the sands, on which the vegetation is heavier. Plate 7, *B*, shows this difference in vegetation on the first ridge north of the crest road in the northwest corner of sec. 3, T. 31 S., R. 24 E. The mudstone in this view is the third one above the base of the upper part of the Tulare formation. The value of the contrast in vegetation as an aid in mapping is forcefully realized in the developed areas, where the vegetation has been cleared off as a precaution against the spread of fire. Even the finest mudstones examined contain relatively coarse detrital material, which consists principally of angular grains of quartz and feldspar and of flakes of mica. At places they are sandy, and an entire bed may grade into silty sand or may lens out between beds of sand.

Almost all these buff mudstones carry thin layers of marlstone or limestone, which usually lie at the top of a bed but may be near the base or middle. Gradations from calcareous mud through marlstone to limestone are apparent in the same bed. These calcareous layers can be traced by the small nodular pieces of marlstone or larger and harder pieces of limestone strewn along the outcrop. Limestone A, the datum bed, is the only relatively thick limestone in the upper part that extends over a considerable area. It generally is not more than 1 foot thick, but the thickness is variable, as the bed pinches and swells in an irregular fashion. Pieces of limestone strewn along the outcrop give the impression that the bed is of uniform thickness, but fresh exposures, such as the cut along the crest road in the southwestern part of sec. 32, T. 30 S., R. 24 E., show that it consists of irregular masses of limestone embedded in mudstone. The mudstone in which it lies is olive-gray, though the rest of the bed is buff. This limestone is either soft and chalky or hard, the latter condition being probably due to secondary cementation. It has a dense earthy appearance and is dirty white or slightly cream-colored. The rock is composed of very fine grained calcite, in which are scattered grains of quartz, rather fresh feldspar, and a few flakes of mica. Small cloudy masses seen in thin sections represent clayey material, and when the rock is treated with acid a relatively large percentage of clayey residue remains. The hard rock is full of minute cavities, many of which are lined with relatively coarse grains of calcite. Clusters of coarse calcite grains probably represent completely filled cavities. A specimen of the limestone collected along the south side of the crest road near the west line of sec. 3, T. 31 S., R. 24 E. (locality plotted on pl. 1), carries scattered broken vegetative remains of *Chara*, a lime-secreting alga that lives in the quiet waters of ponds, lakes, and brackish-water lagoons. These remains, which probably represent both stems and

branchlets, have a length of 3.5 to 4 millimeters. They show hardly any torsion. The diameter of six pieces examined in thin sections ranges from 150 to 450 microns. Forty rows of cortical cells were counted on a section that has a diameter of 400 to 450 microns. Curiously enough these remains are silicified, though the rock itself is not at all silicified. Although the broken stems and branchlets are abundant, not a single node of fruit was found. Strange as this may seem, it is apparently not unusual, for years ago the United States National Museum received from a correspondent at Reno, Nev., a cigar box of material that consisted of nothing but *Chara* internodes and branchlets.

So far as gross features are concerned, the sands lying between the mudstones are very much alike, except that some contain more pebbles than others and the pebbles may represent a greater variety of rocks. The sands are grayish, and most of them are thinner than the mudstones. Unlike the mudstones, they generally are not consolidated. Even in fresh excavations the grains are easily dislodged and can be scooped out by hand, though at places a layer, generally at the base of a bed, may be cemented. Fresh exposures, such as the pit shown in Plate 8, show that the sand is cross-bedded, and wherever the foreset beds could be clearly seen they dip northeastward. All the sands in the upper part, like those in the lower part, carry courses of gravel made up of small pebbles, which appear as pockets and irregular stringers when seen in section. (See pl. 9, *B*.) Pieces of light-colored siliceous shale are the most abundant of the pebbles. Most of these pieces are thin and crudely rectangular and have rounded ends, others are disk-shaped, and others are sharp-edged splinters. Although virtually all the sands contain pieces of siliceous shale, some have a greater proportion of rounded pebbles consisting of granitic and other igneous rocks, chert, quartz, and sandstone. One layer in a bed of sand may contain a variety of relatively coarse pebbles, and another layer in the same bed may contain only small pieces of siliceous shale. Even the largest pebbles are not more than 6 to 8 inches in diameter. The sands lying at the top of the Tulare formation along the south edge of the hills have a greater variety of pebbles than the underlying sands, and the pebbles are larger. Some of these sands form miniature cuestas, and the numerous pebbles lying on the dip slope, which represent a natural gravity concentrate, give an erroneous impression that the beds are gravel. The sand itself varies in texture and in degree of sorting. Much of it is dirty and poorly sorted, but some of it is very clean. It is generally well stratified. The beds of sand contain a large amount of unweathered feldspar. Here and there are very thin black streaks that represent concentrates of heavy minerals.

## LOWER PART

*Stratigraphy.*—The lower part of the Tulare formation, like the upper part, consists of alternating beds of sand and mudstone. In the eastern part of the hills the uppermost mudstone is the highest olive-gray bed. Farther west over a large area on the north slope this mudstone carries at its top limestone B (see pl. 1), which is well exposed in the western part of the area where it was mapped. Plate 9, A, is a view in this area on the east bank of the arroyo along the east line of sec. 16, T. 30 S., R. 23 E., which is taken as the type locality of limestone B. This limestone was not mapped on the north slope east of fault 1, and even immediately west of this fault it has for the most part disappeared. Farther east, however, near the center of the north line of sec. 35, T. 30 S., R. 24 E., between wells No. 36 and No. 35, a limestone is found in the stratigraphic position of limestone B. A limestone at this level also crops out on the south slope in the southern part of sec. 5, T. 31 S., R. 24 E., and on the narrow anticline along the south edge of the hills west of the Carman road. Where limestone B and limestone A are found in the same section the interval between the top of B and the base of A is 50 to 80 feet. A limestone that crops out for a short distance around the southwest corner of sec. 32, T. 30 S., R. 24 E., lies too high for limestone B, as it is only 30 feet below limestone A. Apparently it is a bed that was not found elsewhere, though it is precisely like the other two limestones.

Still lower in the section are other olive-gray mudstones. In the deep ravines that head into the crest of the hills in secs. 31 and 32, T. 30 S., R. 24 E., where the lowest beds in the main folds are exposed, the maximum thickness of the lower part is 250 feet. Along the longest of the narrow anticlines on the south slope the thickness may be greater, but the structure there is obscure.

*Lithology.*—The mudstones in the lower part of the Tulare formation are light olive-gray (23''''''d of Ridgway's "Color standards," or a little darker), but near the top a brownish bed appears here and there. The mudstones that were examined contain a larger proportion of detrital mineral grains than the buff beds, and except in the uppermost bed calcareous layers are not so common or are quite absent. Clusters of gypsum plates are abundant in these gray mudstones.

Limestone B resembles limestone A but is generally thicker, the maximum thickness being fully 3 feet. It varies greatly in thickness, however, like limestone A. (See pl. 9, A.) At several places this limestone is partly silicified and breaks with a sharp-edged conchoidal fracture. The partly silicified rock consists of opal and calcite, and the cavities are lined with chalcedony.

The sands in the lower part of the formation (see pl. 9, *B*) are essentially like those in the upper part, but none that are exposed contain the relatively large assorted pebbles found near the top of the upper part.

The following section measured along the steep slope on the east side of the ridge in the northwestern part of sec. 23, T. 30 S., R. 23 E., shows the lithology of beds at the base of the upper part of the Tulare formation and at the top of the lower part, including limestone B.

*Section of part of Tulare formation in sec. 23, T. 30 S., R. 23 E.*

| Upper part:                                                                                                                                                                                                                    |  | Feet  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|-------|
| Mixture of fine-grained sand and silt; top not exposed                                                                                                                                                                         |  | 36.0  |
| Sand, coarse; contains a greater proportion of pebbles of granitic rock, chert, quartz, and sandstone than the underlying sands                                                                                                |  | 20.5  |
| Mudstone, buff                                                                                                                                                                                                                 |  | 9.8   |
| Sand, coarse, and lenses of fine sand; many small pieces of siliceous shale (maximum length 3 inches) scattered throughout bed and concentrated in irregular layers that appear as pockets; a few small pebbles of other rocks |  | 13.3  |
| Mudstone, buff                                                                                                                                                                                                                 |  | 9.0   |
| Lower part:                                                                                                                                                                                                                    |  |       |
| Sand, granitic, coarse; a few small pebbles, principally siliceous shale                                                                                                                                                       |  | 27.0  |
| Mudstone, buff to olive-gray; carries at top a dirty-white limestone (limestone B) which has a thickness of 3 feet or less; 6 feet above base is a thin band of fine silty sandstone                                           |  | 30.3  |
| Sand, coarse; many disk-shaped pebbles of siliceous shale (maximum length 3 inches) and a few pebbles of other rocks; lower 2 feet at places partly consolidated                                                               |  | 21.6  |
| Mudstone, olive-gray; base not exposed                                                                                                                                                                                         |  | 16.2+ |

**CONCEALED BEDS**

According to well logs, the concealed part of the Tulare formation consists principally of "shales" and sandy "shales," with some relatively thin beds of sand or gravelly sand and a few thin beds that are recorded as "shell," probably representing hard limy layers and thin beds of cemented sand. The number and stratigraphic level of the "shell" beds is not uniform even within small areas. "Boulders" are recorded in most of the logs at various horizons but are not to be taken too seriously. Most of the logs show a pronounced color change from the "yellow shale" in the upper part of wells to the predominant "blue shale" in the lower part, but this change is not uniform.



No definite information is available as to the location of the boundary between the Tulare and Etchegoin formations, for cores are not taken so high in the section. On the assumption that the *Scales* bed lies 2,000 feet below the top of the Etchegoin formation (see p. 39), the thickness of the concealed part of the Tulare formation and the total thickness of the formation are shown in the following table. Inasmuch, however, as the assumption that the *Scales* bed lies at a uniform level below the top of the Etchegoin regardless of location with reference to structural features is unwarranted, a better basis for comparing the thickness of the beds at different places in the hills is afforded by the stratigraphic interval between limestone A and the *Scales* bed, which also is given in the table.

*Thickness in Elk Hills of Tulare formation and of beds lying between limestone A and Scales bed*

| Location                                                                          | Thickness of concealed part of Tulare formation | Total thickness of Tulare formation | Thickness of beds between limestone A and <i>Scales</i> bed |
|-----------------------------------------------------------------------------------|-------------------------------------------------|-------------------------------------|-------------------------------------------------------------|
|                                                                                   | <i>Feet</i>                                     | <i>Feet</i>                         | <i>Feet</i>                                                 |
| Central field, northeastern part of sec. 1, T. 31 S., R. 23 E.-----               | 525                                             | 875                                 | 2,410                                                       |
| Crest of eastern field, northeastern part of sec. 3, T. 31 S., R. 24 E.---        | 790                                             | 1,140                               | 2,780                                                       |
| North edge of eastern part, south line of sec. 22, T. 30 S., R. 24 E.---          | 1,770                                           | 2,370                               | 3,600                                                       |
| South edge of eastern part, northwestern part of sec. 14, T. 31 S., R. 24 E.----- | 2,200                                           | 2,950                               | 4,370                                                       |

#### STRATIGRAPHIC RELATIONS

At the type locality in the Kettleman Hills the Tulare formation conformably overlies the Etchegoin formation. Elsewhere in the Coalinga region the deposits seem to be conformable, but in the Kreyenhagen Hills the Tulare formation overlaps the Etchegoin formation.<sup>16</sup> Along the north slope of the Temblor Range in the Sunset-Midway field the Etchegoin formation is at most places concealed by the overlap of the Tulare formation, which may rest directly on the Maricopa shale,<sup>17</sup> though otherwise there is no marked evidence of unconformity between the Tulare and Etchegoin.<sup>18</sup>

#### FOSSILS

During the field work in 1924 a few vertebrate fossils were collected from the buff mudstone at the base of the upper part of the Tulare formation on the west slope of the ridge in the western part of sec. 4, T. 31 S., R. 24 E. Another specimen was found by R. D. Reed in

<sup>16</sup> Arnold, Ralph, and Anderson, Robert, Preliminary report on the Coalinga oil district, Fresno and Kings Counties, Calif.: U. S. Geol. Survey Bull. 357, p. 60, 1908; Geology and oil resources of the Coalinga district, Calif.: U. S. Geol. Survey Bull. 398, p. 149, 1910.

<sup>17</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 46, 50, 1920.

<sup>18</sup> Idem, pp. 44, 47.

1925 in limestone A at the cut along the crest road in the southwestern part of sec. 32, T. 30 S., R. 24 E. Both these localities are shown on Plate 1. This material was examined by J. W. Gidley, of the United States National Museum. It consists of remains of a camel (*Procamelus?*), a rabbit (*Lepus*), and a wood rat (*Neotoma*), found in the mudstone, and a cotton rat (*Sigmodon*), found in the limestone. According to Gidley, the material is too scanty to determine the species. In an oral communication J. H. Menke, of the Standard Oil Co., reports that several horse teeth, which passed into the possession of a drilling foreman, were collected in an excavation near well 110, in sec. 35, T. 30 S., R. 24 E., and a large flat bone was found in an excavation near well 75, in the same section. These finds indicate that the Elk Hills offer a promising field for collecting vertebrate fossils, which would fill a gap in the succession of vertebrate faunas on the Pacific coast. A peculiar dog (*Hyænognathus pachyodon* Merriam<sup>19</sup>) and a saber-tooth cat (*Ischyrosmilus ischyrus* (Merriam)<sup>20</sup>) are the only vertebrates heretofore recorded from the Tulare formation. Though the age of the beds near McKittrick that yielded these fossils was not definitely known when they were collected, they are now regarded as representing the Tulare formation.<sup>21</sup>

*Chara* remains that were discovered in limestone A have already been mentioned in the description of the upper part of the Tulare formation. Silicified wood was found in the upper part of the formation in the SW.  $\frac{1}{4}$  sec. 19, T. 30 S., R. 23 E.

So far no invertebrate fossils have been found in the beds that crop out in the Elk Hills. Fresh-water mollusks are very abundant in part of the Tulare formation of the Kettleman Hills, and they have also been recorded near McKittrick. G. D. Hanna<sup>22</sup> reports that *Anodonta*, *Valvata*, *Amnicola*, and other fresh-water fossils have been recovered from ditch samples in the Elk Hills.

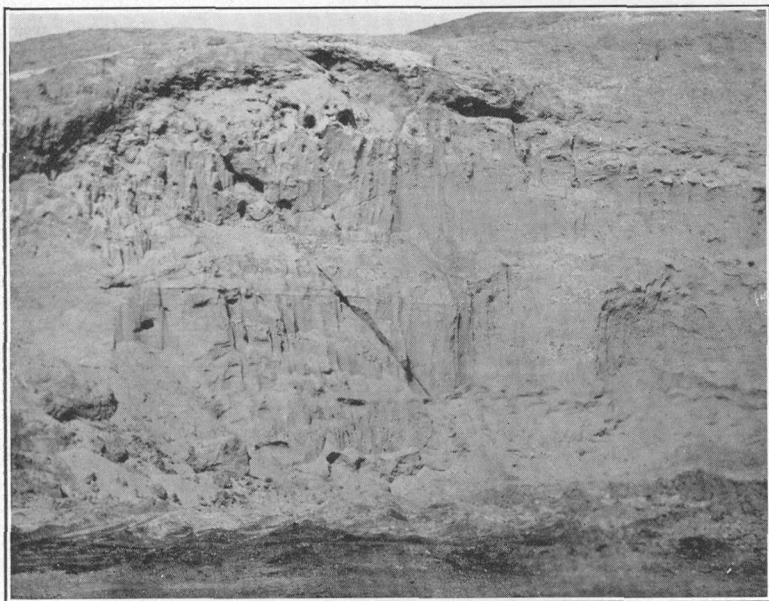
Pearly mussels, represented generally by finely broken pieces, were found lying on the surface at many places near the east end of the hills. Scattered pieces were seen as much as 6 miles from the east end, but they are most abundant within 1 or 2 miles of the east end. At places the ground is littered with broken shell flakes. Pieces of shells may be seen also along the highway that skirts the east end of the hills. A few complete or nearly complete specimens that were

<sup>19</sup> Merriam, J. C., The Pliocene and Quaternary Canidae of the Great Valley of California: California Univ. Dept. Geology Bull., vol. 3, pp. 277-290, pls. 28-30, 1903.

<sup>20</sup> Merriam, J. C., A new sabre-tooth cat from California: California Univ. Dept. Geology Bull., vol. 4, pp. 171-175, 1 fig., 1905. See also Merriam, J. C., Relationships of Pliocene mammalian faunas from the Pacific coast and Great Basin provinces of North America: California Univ. Dept. Geology Bull., vol. 10, p. 425, 1917.

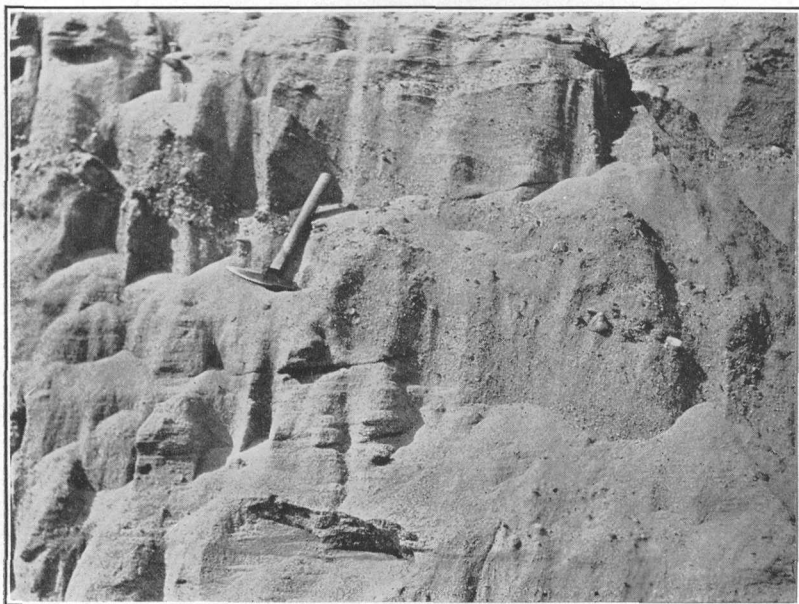
<sup>21</sup> Russell, R. D., and Vander Hoof, V. L., A vertebrate fauna from a new Pliocene formation in northern California: California Univ. Dept. Geol. Sci. Bull., vol. 20, No. 2, p. 20, 1931.

<sup>22</sup> Written communication.



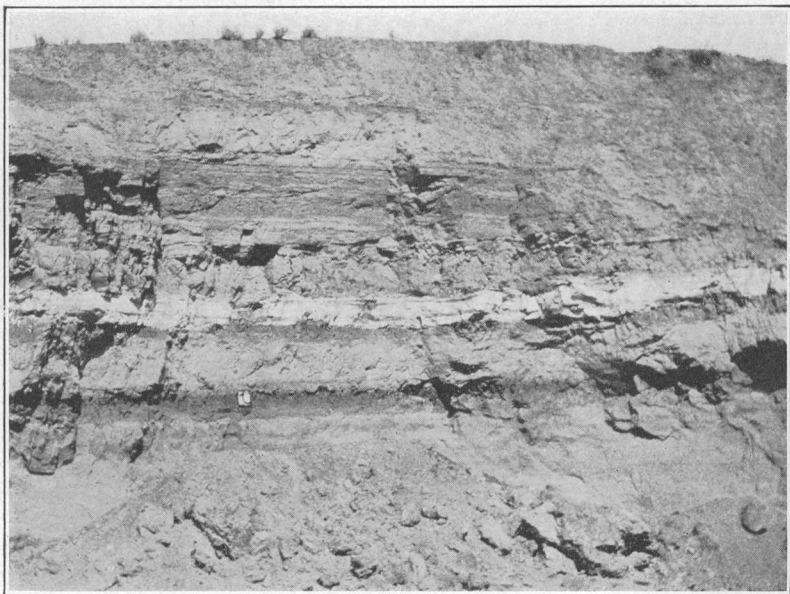
A. SAND PIT ALONG EAST SIDE OF CREST ROAD IN NORTHEASTERN PART  
OF SEC. 3, T. 31 S., R. 24 E.

This bed lies between the second and third mudstones in the upper part of the Tulare formation.  
Note the joints in this unconsolidated sand.



B. CLOSER VIEW OF PART OF SAME PIT, SHOWING IN GREATER DETAIL CROSS-  
BEDDING AND GRAVEL LAYERS

SAND IN UPPER PART OF TULARE FORMATION



A. SAND, MUDSTONE, AND LIMESTONE IN LOWER PART OF TULARE FORMATION AS EXPOSED ALONG EAST SIDE OF STREAM ALONG EAST LINE OF SEC. 16, T. 30 S., R. 23 E.

The white band in middle of view is limestone B as exposed at its type locality. Note how it pinches and swells. Here it has a maximum thickness of  $2\frac{1}{2}$  feet. Collecting bag in lower left has a length of 1 foot.



B. SAND IN LOWER PART OF TULARE FORMATION EXPOSED ON EAST SIDE OF STREAM IN SEC. 19, T. 30 S., R. 23 E.

The gravel courses appear as irregular pockets and stringers.

#### TULARE FORMATION IN ELK HILLS

collected in the hills were examined by W. B. Marshall, of the United States National Museum, who reports that they represent *Anodonta wahlametensis* Lea and *Gonidea angulata* Lea. Both these species are now living in California, and they probably could be found in Buena Vista Lake and in the canals that enter and drain it. The presence of these shells only at the east end of the hills, close to the only permanent bodies of water, indicates that they were carried there. If so, it must have been long ago, for all the shells are bleached and have lost the epidermis. Perhaps they were carried in by Indians, who are known to have used fresh-water mussels as food in the interior of California, but this view can not be regarded as substantiated until potsherds or charcoal are found with the shells. At all events these shells are not regarded as fossils.

#### AGE

The Tulare formation itself has not yet yielded any conclusive evidence as to its age. In the Coalinga region the underlying Etchegoin formation carries near its top a horse of the genus *Plesippus*, found also in the middle Pliocene Blanco formation of Texas. (See p. 39.) In view of this evidence, it seems probable that the Tulare formation, in the type region at least, is of late Pliocene age or straddles the Pliocene-Pleistocene boundary.

#### CONDITIONS OF DEPOSITION

The lithology of the Tulare formation varies from place to place around the edge of San Joaquin Valley, depending on the kind of material that furnished the sediments and the conditions under which they were laid down. On Wheeler Ridge and at other places in the foothills of the San Emigdio Mountains it carries gravel consisting of large cobbles and boulders of granitic and other igneous rocks derived directly from the San Emigdio Mountains or by way of earlier coarse detrital beds.<sup>23</sup> These beds are much coarser than any found in the Elk Hills. The thin-bedded and relatively well-sorted material found in the Tulare formation of the Kettleman Hills is absent in the Elk Hills. As Pack<sup>24</sup> has pointed out, probably all the sediments of the Tulare formation in the Elk Hills and near-by regions were derived from the early Temblor Range. The Maricopa shale, which crops out in extensive areas in the present Temblor Range, is the only apparent source of the pieces of light-colored siliceous shale that are very abundant in the Tulare sands. Detrital

<sup>23</sup> Hoots, H. W., Geology and oil resources along the southern border of San Joaquin Valley, California: U. S. Geol. Survey Bull. 812, pp. 289-291, 1930.

<sup>24</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, p. 49, 1920.

beds in the Maricopa shale, particularly in the upper part, seem to be the source of the pebbles of granitic and other rocks in the sands and of the arkosic material of varying size in the sands and mudstones. The clayey material evidently was derived principally from the Maricopa shale, both by the grinding of pieces of hard shale during transportation and directly from the mud shales and the diatomite, of which the diatomite weathers at the outcrop to a dustlike powder.

Everywhere in the Elk Hills the rocks consist of alternating beds of sand and mudstone that have an estimated average thickness of 10 to 25 feet. Clean contacts were not seen at many places, but the change at the top of a bed of mudstone is generally more abrupt than that at its base. The sands are cross-bedded, the foreset beds dipping to the northeast wherever they were clearly seen, and they carry a complex pattern of gravel courses that appear in section as irregularly arranged stringers or as pockets (see pl. 9, *B*), depending on the angle between the plane of the section and the direction of their trend. These sands were clearly laid down by streams. They are not confined to channels but are spread over a large area, perhaps as large as the hills themselves, but no one bed was traced over so large an area; and despite the different kinds of material they are very uniform, for they are composed of clean sand, dirty sand, and fine gravel. They have the appearance of deposits laid down as alluvial fans by ephemeral streams on the slope leading down from the mountains to the valley. Gravel courses deposited in shallow interlacing channels on alluvial fans, viewed in random sections, have precisely the appearance of the gravel layers in the Tulare sands. A particularly clear account of the building of alluvial fans is given by Johnson<sup>25</sup> in his report on the High Plains, and Trowbridge<sup>26</sup> has described the significance of the pocketlike appearance of gravel courses when viewed in section.

The beds of mudstone are thick, massive, and relatively uniform in composition, but their areal extent is not so great as that of the sands. At many places a mudstone lenses out between beds of sand. In view of the absence of thin beds of well-sorted material of different sizes, such as are found in the Kettleman Hills, these muds apparently were not laid down in permanent lakes. They probably were deposited on mud flats at the foot of the slope of alluvial fans where flood water spread out and laid down the fine material brought down by the streams. The limy layers and the *Chara* remains found in one of the limestones point to frequent flooding of the mud flats, forming shallow temporary lakes, or playas, in which the water partly

<sup>25</sup> Johnson, W. D., The High Plains and their utilization: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 4, pp. 612-656, pls. 113-146, figs. 300-329, 1901.

<sup>26</sup> Trowbridge, A. C., The terrestrial deposits of Owens Valley, Calif.: Jour. Geology, vol. 19, pp. 743-744, 1911.

evaporated and deposited the calcareous material held in solution. The source of the lime may confidently be attributed to the limestones in the Maricopa shale. Streams flowing over this shale are known to take up a large amount of lime in solution. The limy layers are nodular, like the caliche deposited by evaporating ground water, but they are confined to definite layers in the muds. So far as known the muds contain no saline material, except the clusters of gypsum plates in the olive-gray beds, which are probably of secondary origin. It is assumed that the playas were drained by either underground or surface drainage before evaporation proceeded far enough to cause the deposition of saline material or that the deeper parts of the playas, where water was completely evaporated, lay farther out in the valley beyond the present site of the Elk Hills. These muds are very plastic, and the absence of lamination due to successive increments and of mud cracks is apparently to be attributed to their swelling when moistened by the next flooding. Much of the fine material may have been picked up by winds in the mountains, where beds in the Maricopa shale that weather to a fine powder crop out, and then carried into the valley by dust storms similar to those that now frequently sweep over the region. Moist mud flats would effectively catch such material. The olive-gray color characteristic of the muds in the lower part of the Tulare formation is generally regarded as an indication of reduced iron. It should be noted that the limestones of the buff mudstones, which clearly represent a relatively long period of standing water, are embedded in olive-gray mud, and that remains of the cotton rat, which in the Western States now lives in relatively moist places where grass and tule afford cover, were found in a limestone. If this indirect evidence that abundant plant debris caused the reduction of the iron is accepted, the inference follows that the buff muds of the upper part of the formation were laid down under a more arid climate, possibly during an interglacial period, than the olive-gray muds of the lower part, which may represent a glacial period. A similar succession of "grayish green" clay overlain by "yellowish" clay is recorded by Buwalda<sup>27</sup> in the Manix lake beds of the Mohave Desert, which are referred to the Pleistocene.

It is quite certain that the sands are alluvial-fan deposits, and it is reasonably certain that the muds are mud-flat and playa deposits. The most striking thing about these beds in the Elk Hills is the alternation of thick beds of the two kinds of deposits—a feature that made their mapping possible. The beds are too thick to attribute the alternation to seasonal control. The sorting is too uni-

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<sup>27</sup> Buwalda, John P., Pleistocene beds at Manix in the eastern Mohave Desert region: Calif. Univ. Dept. Geology Bull., vol. 7, No. 24, p. 449, 1914.

form and relatively too perfect, and the alternation is on too large a scale to attribute it to the overlapping of material laid down on different zones of adjoining fans of varying size on a slope made up of coalescing fans. If the conclusions as to mode of deposition are accepted, it is necessary to postulate conditions under which fans and mud flats alternated at the same place—that is, conditions which affected the kind of material that the streams could transport, by controlling either their gradient or the supply of material. An assumption of periodic changes in climate would meet the requirements. At the time when these deposits were laid down San Joaquin Valley lay in the lee of the Coast Ranges, and there is no reason to doubt that the climate then was semiarid. Only slight changes in the degree of aridity need be postulated, but such an assumption of climatic control seems fantastic without supporting evidence. Perhaps the simplest and most reasonable hypothesis is an assumption of periodic elevation of the adjoining mountains that controlled the gradient of the streams and thereby the kind of material they could carry. That the change in character of the streams was pronounced enough not only to cause gravel-coursed sands to be spread out where muds were formerly deposited but even to channel the hardened mud is indicated by the distribution of limestone A in sec. 6, T. 31 S., R. 24 E., and in the southern part of sec. 31, T. 30 S., R. 24 E., immediately north. On at least eight spurs the limestone is abruptly cut off by sand. (See pl. 1.) This is not a matter of poor exposures or slumping, for it is clearly seen on south slopes where exposures are satisfactory; nor is it due to faulting, for an underlying bed of mudstone and at places an overlying bed are unaffected. This abrupt cutting off of the limestone and of the mudstone that carries it seems to mark the edge of a stream channel, which can not be traced northward on account of the poor exposures on the north slope of the crest ridge. The disappearance of the same mudstone and limestone in the southeast corner of section 31 may indicate the position of the east margin of this channel. Perhaps the absence of the bed mapped as the base of the upper part of the Tulare formation near the county road in the southwestern part of sec. 28, T. 30 S., R. 23 E., where it is shown on Plate 1 as a broken line, though it is well exposed to the east and west, is to be attributed to channeling, but the exposures are inconclusive. The sand certainly accumulated more rapidly than the mud, but the mudstones are as thick as the sands—indeed, almost throughout the section they are thicker than the sands. On the hypothesis of periodic elevation of the mountains this would mean that relatively long periods intervened between the uplifts. Whether the physiographic history of the Temblor Range would bear out this hypothesis is not now known.



## TERTIARY DEPOSITS

## ETCHEGOIN FORMATION

## LITHOLOGY AND THICKNESS

The beds that yield the oil of the Elk Hills field are in the upper part of the Etchegoin formation, which underlies the Tulare formation. The type locality of the Etchegoin formation is along the foot of the Diablo Range north of Coalinga. Extensive areas of this formation are found in the Coalinga region along the flank of the Diablo Range and in the foothills. Farther south along the foot of the Temblor Range outcrops have been found at only a few places, presumably owing to the thinness of the deposits and to the overlap of the Tulare formation. Larger areas have been mapped in the foothills of the San Emigdio Mountains.

As described by Pack,<sup>28</sup> the Etchegoin formation at the outcrops in the Sunset-Midway field consists of imperfectly consolidated sand, pebbly sand, and clay. At places the beds are indurated by the addition of calcareous cement. Most of these beds were laid down in marine waters, and some of them carry many marine fossils. The sands are fine or coarse, are arkosic, and carry layers containing pebbles that represent a variety of rocks, though pieces of white siliceous shale are most abundant. The clays are sandy and carry lenses of fine sand or coarse pebbly sand.

According to well records and cores, the Etchegoin formation underlying the Elk Hills consists of deposits similar to those at the outcrop, but the material is finer, and very few pebbly beds are recorded. The clays are of varying somber shades of green and greenish gray, but they appear bluish when wet and are logged as "blue shale." Cores that are taken in and above the oil zone consist of olive-green clay, sandy clay, and thin beds of unconsolidated or imperfectly consolidated sand. These beds lie about 2,000 feet below the top of the Etchegoin formation. Most of the material in the overlying part of the formation is logged as "blue shale" and "blue sandy shale." Sands of varying thickness lie between these thick beds of "shale." A few thin hard beds, which can not be recognized from well to well, are recorded as "shell."

According to the figures already given for the Tulare formation, the thickness of the Etchegoin formation above the *Scales* bed, which lies immediately above the main oil zone of the eastern field or is separated from it by an interval of as much as 35 feet, is assumed to be 2,000 feet. The thickness of beds between the *Scales* bed and limestone A (see table, p. 25) indicates, however, that the

<sup>28</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 44-47, 1920.

part of the Etchegoin lying above the *Scales* bed is considerably thicker along the edge of the hills than on the crest.

The producing wells in the eastern field are drilled to a depth below the *Scales* bed of 30 to 285 feet. Well No. 10, in sec. 31, T. 30 S., R. 25 E., shows a thickness of about 1,300 feet of Etchegoin deposits lying below the *Scales* bed. Slater No. 1, a dry hole in sec. 22, T. 30 S., R. 24 E., at the north edge of the hills, records a thickness of almost 1,700 feet of Etchegoin deposits below the *Scales* bed. Well No. 27, in sec. 31, T. 30 S., R. 25 E., was drilled in 1928-29 as a deep test well and is reported to have reached the Maricopa shale, but data on this well are not available for publication. It is estimated that in the deepest well in the central field the thickness of the Etchegoin formation below the *Scales* bed is 800 feet, though it may be considerably more. In both fields the beds below the *Scales* bed are logged as "blue shale" and "blue sandy shale," with some sands. These figures are uncertain because the top of the Etchegoin formation is not definitely located, but the thickness of the Etchegoin formation apparently is about 7,000 feet.

#### FOSSILS

At the outcrop the Etchegoin formation carries many fossils, particularly in the Coalinga region, where it was first described. The marine fossils consist principally of mollusks<sup>29</sup> and echinoids,<sup>30</sup> and the nonmarine fossils embrace a number of mammals.<sup>31</sup>

Marine and fresh-water fossils (foraminifers, mollusks, ostracodes, and fish bones and scales) are also found in the Etchegoin formation of the Elk Hills, and some beds are crowded with them. The highest

<sup>29</sup>Arnold, Ralph, Paleontology of the Coalinga district, Fresno and Kings Counties, Calif.: U. S. Geol. Survey Bull. 396, pp. 22-45, 63-90, pls. 11-29, 1909. Nomland, J. O., Relation of the invertebrate to the vertebrate faunal zones of the Jacalitos and Etchegoin formations in the north Coalinga region, Calif.: California Univ. Dept. Geology Bull., vol. 9, pp. 77-88, pl. 7, 1916; Fauna from the lower Pliocene at Jacalitos Creek and Waltham Canyon, Fresno County, Calif.: Idem, vol. 9, pp. 199-214, pls. 9-11, 1916; The Etchegoin Pliocene of middle California: Idem, vol. 10, pp. 191-254, pls. 6-12, 2 figs., 1917.

<sup>30</sup>Kew, W. S. W., Cretaceous and Cenozoic Echinoidea of the Pacific coast of North America: California Univ. Dept. Geology Bull., vol. 12, pp. 23-236, 40 pls., 5 figs., 1920.

<sup>31</sup>Merriam, J. C., Correlation between the Tertiary of the Great Basin and that of the marginal marine province in California: Science, new ser., vol. 40, pp. 643-645, 1914; Tertiary vertebrate faunas of the north Coalinga region of California, a contribution to the study of paleontologic correlation in the Great Basin and Pacific coast provinces: Am. Philos. Soc. Trans., new ser., vol. 22, pp. 191-234, 49 figs., 1915; New horses from the Miocene and Pliocene of California: California Univ. Dept. Geology Bull., vol. 9, pp. 49-58, 12 figs., 1915; Relationship of *Equus* to *Pliohippus* suggested by characters of a new species from the Pliocene of California: Idem, vol. 9, pp. 525-534, 18 figs., 1916; Relationship of Pliocene mammalian faunas from the Pacific coast and Great Basin provinces of North America: Idem, vol. 10, pp. 421-443, 1 fig., 1917. Kellogg, Louise, A fossil beaver from the Kettleman Hills, Calif.: California Univ. Dept. Geology Bull., vol. 6, pp. 401-402, 3 figs., 1911.

marine beds, which in the eastern field lie perhaps as much as 2,000 feet above the *Scalez* bed, are above the depth at which coring is begun. These beds, as reported by G. D. Hanna,<sup>32</sup> carry a few fossils, of which *Mya* is the most common. In the lower part of this series is found a foraminifer, described as a variety of *Elphidium hughesi* Cushman and Grant<sup>33</sup> and representing a genus more familiarly known by the Lamarckian name *Polystomella*. It is recorded by Cushman and Grant from well No. 89, in sec. 35, T. 30 S., R. 24 E., at a depth of 2,845 feet, or 140 feet above the estimated depth of the *Scalez* bed, and also from the type locality of the Purisima formation. This part of the section consists of alternating marine and nonmarine beds, and the sparse representation of foraminifers is to be attributed to the low salinity of the water. Marine fossils (*Elphidium*, ostracodes, *Nassarius*, *Mytilus*, and *Mya*) are found in the upper oil sand. The succession of fossiliferous beds lying immediately above and within the main oil zone of the eastern field, shown in Figure 5, is well known through coring and has been outlined by Roberts.<sup>34</sup> The first *Amnicola* bed carries many small fresh-water gastropods of the genus *Amnicola*. Other beds in this zone of fresh-water deposits carry additional fossils, among which the gastropod *Valvata*, the mussel *Anodonta*, smooth ostracodes, and fish bones and scales have been recognized,<sup>35</sup> the ostracodes being particularly abundant in a thin bed immediately above the *Scalez* bed. Below these fresh-water beds both marine and fresh-water fossils are found. In the adjoining Sunset-Midway field many marine fossils have been found in the lower part of the Etchegoin formation,<sup>36</sup> but no records are available for the Elk Hills.

The peculiar fossils in the *Scalez* bed are more readily recognized than any of the others. This distinctiveness and their great abundance in a bed of characteristic brittle texture that has a thickness of only 1 to 6 feet make them the most useful guide fossils. They were first discovered by F. E. O'Neill while he was on the staff of the Pacific Oil Co. In December, 1921, well No. 23 of the Pacific Oil Co., in sec. 35, T. 30 S., R. 24 E., blew out while shutdown for repairs. Mr. O'Neill discovered that pieces of rock blown out of this well carried curious calcareous plates. Similar plates were blown out of well

<sup>32</sup> Written communication.

<sup>33</sup> Cushman, J. A., and Grant, U. S., Late Tertiary and Quaternary Elphidiids of the west coast of North America: San Diego Soc. Nat. Hist. Trans., vol. 5, No. 6, pp. 75-76, pl. 7, figs. 4 a, b, 1927.

<sup>34</sup> Roberts, D. C., Fossil markers of Midway-Sunset-Elk Hills region in Kern County, Calif.: California State Mining Bur. Summary Operations California Oil Fields, vol. 12, No. 10, pp. 5-10, 4 pls., 1927.

<sup>35</sup> Hanna, G. D., written communication.

<sup>36</sup> See Goudkoff, P. P., Correlative value of the microlithology and micropaleontology of the oil-bearing formations in the Sunset-Midway and Kern River oil fields: Am. Assoc. Petroleum Geologists Bull., vol. 10, pp. 482-494, 4 figs., 1926.

No. 9, in the same section, in June, 1922. During May and later months of 1923 Mr. O'Neill, then on the staff of the Pan American Petroleum Co., found these fossils in cores taken in several wells in sec. 34, T. 30 S., R. 24 E., and sec. 3, T. 31 S., R. 24 E. He soon discovered that the bed carrying them lay at a virtually uniform distance above the main oil zone and successfully exploited this guide in landing the water string. During this time these fossils were logged as "fish scales" and later as "resinous fish scales." In March, 1924, Hanna and Gaylord<sup>37</sup> described them under the name *Scalez petrolia* and suggested that they are opercula of a shell-less or chitinous-shelled gastropod, for at that time no shells that could contain opercula of this size had been found.

Specimens of *Scalez petrolia* are shown on Plate 10. These fossils have a "length," measured along the longest diameter, of 6.2 to 8.7 millimeters and a "width" of 4.5 to 7 millimeters. They are composed of very thin calcareous laminae that are very fragile and readily peel off. One surface is concave and the other is convex. As the rock naturally splits along the convex surface, it is difficult to expose the concave surface. An eccentric nucleus, around which the laminae are concentrically arranged, lies close to one side. It has already been suggested that these fossils are very similar in shape to opercula of living pond snails of the genus *Viviparus*.<sup>38</sup> The figures of *Scalez* and of opercula of living species of *Viviparus* on Plate 10 show that there is no reasonable doubt that the fossils are gastropod opercula. *Scalez* and *Viviparus* opercula have essentially the same shape—one surface is concave and the other is convex; concentric growth lines encircle the nucleus; on the concave surface, which is the exterior one on the opercula, a narrow thickened ridge lies between the columellar edge and the area where the foot was attached; and the attachment area is slightly roughened. In the fossils, however, the nucleus lies a little closer to the columellar edge. Moreover, *Scalez* is calcareous, whereas the living species of *Viviparus* and its allies have horny opercula. Many of the largest specimens of *Scalez petrolia* are of approximately the same size, indicating that they are opercula of adult shells. According to the figures on Plate 10 the fossils are a little less than half as large as opercula from adult shells of species of *Viviparus* living in the eastern United States.

After *Scalez petrolia* was described Hanna discovered in cores several broken specimens that probably represent the shell of this

<sup>37</sup> Hanna, G. D., and Gaylord, E. G., Description of a new genus and species of freshwater mollusks (*Scalez petrolia*) from the Etchegoin Pliocene of California: California Acad. Sci. Proc., ser. 4, vol. 13, pp. 147-149, 2 figs., 1924.

<sup>38</sup> Woodring, W. P., Pliocene *Viviparus*-like opercula from California: Nautilus, vol. 39, No. 4, pp. 109-111, 1926.

animal. The core from which the specimens reproduced as Figures 1 and 2 on Plate 10 were extracted contains several of these broken crushed shells. They are very thin and imperforate and are marked by fine but conspicuous growth lines. At the aperture the body whorl has a height of 8.5 to 11 millimeters, but the shells are flattened, and the height is a little exaggerated. So far as these crushed fragments go they are very much like shells of a relatively small *Viviparus*. No opercula were found in the apertures of these shells.

Although African and Oriental representatives of the apple shells of the family "Ampullariidae" have an operculum with a thick internal calcareous layer, the resemblance of *Scaez* to the much larger opercula of these tropical shells is too remote, aside from the difference in geographic distribution, to deserve consideration. Nor can the suggestion that *Scaez* is similar to *Bythinia*<sup>39</sup> be taken seriously, for the operculum of *Bythinia* has a central nucleus.

The evidence furnished by the opercula and the less satisfactory evidence based on the few broken crushed shells lead to the conclusion that these fossils, to which the rather barbarous generic name *Scaez* was given in token of their popular designation as fish scales, represent an extinct genus of the family Viviparidae, despite the fact that living Viviparidae have horny opercula. Other families, such as the fresh-water Amnicolidae and "Ampullariidae" and the marine Naticidae, embrace genera with horny opercula and also genera with calcareous opercula. It has been discovered that similar *Viviparus*-like calcareous opercula have been found in beds of supposed Carboniferous age in Nevada which are probably much younger than Carboniferous and in Upper Cretaceous and Eocene deposits in Montana.<sup>40</sup> At the present time *Viviparus* has an extensive distribution in the streams and lakes of the eastern United States, but no native species is living west of the Rocky Mountains.<sup>41</sup> An Eocene species, the operculum of which is unknown, is recorded from Washington,<sup>42</sup> but apparently the genus has not been found in later Tertiary deposits on the Pacific coast.

The concentration of opercula and the scarcity or absence of shells is not an unusual feature. Pilsbry<sup>43</sup> has called attention to a record

<sup>39</sup> Hanna, G. D., and Gaylord, E. G., op. cit., p. 149.

<sup>40</sup> Woodring, W. P., Fossil *Viviparus*-like calcareous opercula: *Nautilus*, vol. 40, No. 1, pp. 12-14, 1926.

<sup>41</sup> See Prashad, B., Recent and fossil Viviparidae, a study in distribution, evolution, and palaeogeography: *Indian Mus. Mem.*, vol. 8, No. 4, pp. 153-251, pl. 19, 1928.

<sup>42</sup> Hannibal, Harold, A synopsis of the Recent and Tertiary fresh-water Mollusca of the Californian province: *Malacol. Soc. London Proc.*, vol. 10, p. 194, 1912.

<sup>43</sup> Pilsbry, H. A., Opercula in shore deposits: *Nautilus*, vol. 40, No. 2, p. 69, 1926.

of a concentration of the calcareous opercula of *Bithynia tentaculata* along the shores of a lake in southern Ireland, and according to Kendall <sup>44</sup> these opercula are the only molluscan remains in a Pleistocene peat deposit in Sussex. Calcareous opercula without suitable shells are abundant even in the early Ordovician.<sup>45</sup> The occurrence of aptychi, which are regarded as ammonite opercula, in beds that carry no ammonite shells and the concentration of parts of a fossil that may be dismembered, such as the cephalia and pygidia of trilobites, are further examples. Though such examples are familiar enough, they call for special conditions. It would be unprofitable to speculate as to the conditions under which the opercula of *Scaez* were concentrated until more is known about the distribution of opercula and shells. The extensive distribution of opercula of *Scaez*, as outlined in succeeding paragraphs, in beds that carry very few shells or none at all shows quite conclusively, however, that their concentration is not in the form of narrow windrows due to sorting by wavelets on the shore of a body of water, as in the concentration of opercula of *Bythinia tentaculata* on the shore of the Irish lake.

So far *Scaez* has been found only in cores or cuttings, but it is reasonable to assume that shells and opercula will eventually be discovered in outcrops of nonmarine beds in the upper part of the Etchegoin formation. Since it was first discovered it has been found in almost all wells in the Elk Hills in which cores have been taken at the proper depth, though it has been missed in a few wells in which core recovery was unsatisfactory. It has also been found elsewhere over a large area from Maricopa Flat northward into San Joaquin Valley, as shown by the records in the following table. In addition to the records tabulated specimens from an undetermined depth were blown out of the gas well of the Main Oil Co. on Semitropic Ridge in sec. 28, T. 27 S., R. 24 E., about 4 miles southwest of Wasco.

That the mere presence of *Scaez* is not an infallible stratigraphic guide, however, is indicated by the discovery that they are found at more than one horizon. Available records of wells in which more than one *Scaez*-bearing bed was cored and also records of some outlying wells are as follows:

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<sup>44</sup> Kendall, C. E. Y., Occurrence of opercula in shore deposits: *Nautilus*, vol. 40, No. 3, pp. 99-100, 1927.

<sup>45</sup> Ulrich, E. O., Revision of the Paleozoic systems: *Geol. Soc. America Bull.*, vol. 22, p. 665, 1911.

*Scalez-bearing beds in Buena Vista Hills, Elk Hills, and western San Joaquin Valley*

| Well                                       | Location                                                   | Altitude<br>(feet<br>above<br>sea<br>level) | Depth below surface of Scalez-<br>bearing beds (feet) |                  |        |                          | Stratigraphic interval<br>between beds (feet) |                  |                  |
|--------------------------------------------|------------------------------------------------------------|---------------------------------------------|-------------------------------------------------------|------------------|--------|--------------------------|-----------------------------------------------|------------------|------------------|
|                                            |                                                            |                                             | Bed 1                                                 | Bed 2            | Bed 3  | Bed 4<br>(Scalez<br>bed) | Bed 1<br>to 2                                 | Bed 2<br>to 4    | Bed 1<br>to 4    |
| Honolulu:                                  |                                                            |                                             |                                                       |                  |        |                          |                                               |                  |                  |
| No. 15.....                                | Eastern Buena Vista Hills, sec. 8, T. 32 S., R. 24 E.      | 908                                         | 2, 212                                                | 2, 250           |        |                          | 38                                            |                  |                  |
| No. 39.....                                | do.                                                        | 804                                         | 2, 680                                                | 2, 725           |        |                          | 45                                            | 425              | 470              |
| No. 19.....                                | do.                                                        | 793                                         | 2, 816                                                | 2, 855           |        |                          | 39                                            | 441              | 480              |
| No. 7.....                                 | do.                                                        | 823                                         | 2, 560                                                | 2, 600           |        |                          | 40                                            |                  |                  |
| No. 20.....                                | do.                                                        | 795                                         | 2, 748                                                | 2, 788           |        |                          | 40                                            |                  |                  |
| No. 48.....                                | do.                                                        | 838                                         | 2, 475                                                | 2, 524           |        |                          | 49                                            |                  |                  |
| No. 49.....                                | do.                                                        | 821                                         | 2, 633                                                | 2, 682           |        |                          | 49                                            |                  |                  |
| Standard Oil Co., Pacific No. 40.....      | Eastern Buena Vista Hills, sec. 17, T. 32 S., R. 24 E.     | 773                                         | 2, 910                                                |                  |        |                          |                                               |                  | 470              |
| Ohio Oil Co., Pyramid No. 1.....           | East end of Buena Vista Hills, sec. 20, T. 32 S., R. 25 E. | 331                                         | 4, 206                                                | 4, 256           |        |                          | 50                                            | 924              | 974              |
| Standard Oil Co., Kern County, No. 27..... | East end of Elk Hills, sec. 31, T. 30 S., R. 25 E.         | 501                                         | ( <sup>a</sup> )                                      | ( <sup>a</sup> ) |        |                          | ( <sup>a</sup> )                              | ( <sup>a</sup> ) | ( <sup>a</sup> ) |
| McAdams Petroleum Corp., No. 1.....        | North of west end of Elk Hills, sec. 2, T. 30 S., R. 22 E. | 620                                         | 2, 578                                                |                  |        |                          |                                               |                  | 830              |
| Nordon Oil Corp., Salisbury No. 1A.....    | Buttonwillow Ridge, sec. 7, T. 29 S., R. 24 E.             | 305                                         |                                                       |                  | 3, 234 |                          |                                               |                  |                  |
| Richfield Oil Co., Redding No. 1.....      | Semitropic Ridge, sec. 36, T. 27 S., R. 23 E.              | 295                                         | 3, 869                                                |                  |        |                          |                                               |                  | 876              |
| Shell Oil Co., Williams No. 1.....         | Semitropic Ridge, sec. 17, T. 27 S., R. 23 E.              | 287                                         | 3, 895                                                |                  |        |                          |                                               |                  | 811              |
| Richfield Oil Co., Kerwin No. 1.....       | Semitropic Ridge, sec. 21, T. 26 S., R. 22 E.              | 243                                         | 4, 508                                                |                  |        |                          |                                               |                  |                  |

<sup>a</sup> Figures not available.

Though as many as four beds have been found in one well, the lowermost one (No. 4 of the table) is clearly recognizable as the *Scaletz* bed of the Elk Hills, or the *Scaletz* marker bed, as it is called by the oil operators. It is a thin, brittle greenish-brown shale crowded with *Scaletz*; it lies near the top of the B oil zone as defined by Pack,<sup>46</sup> and it carries virtually no other fossils. *Scaletz* is less abundant in the other beds. In any region the interval between the uppermost bed carrying *Scaletz* and the *Scaletz* bed varies considerably, depending principally on the location with reference to the crests of anticlines. In the Buena Vista and Elk Hills it is least (470 to 480 feet) on or near the crest, greater down the flank or plunge, and still greater (830 to 974 feet) off anticlinal folds.

Cores were taken in only one well in the Elk Hills (Standard Oil Co., Kern County No. 27) at depths that would reveal the upper *Scaletz*-bearing beds. The value of this fossil to the oil operator there depends on the absence of more than one bed near the top of the main oil zone. It is difficult to understand this distribution. *Scaletz* is not found in other parts of the zone of fresh-water beds in which it occurs, some of which are crowded with other fresh-water fossils, particularly *Amnicola* and ostracodes. The *Scaletz* bed clearly represents some unusual conditions, such as a season of heavy rainstorms that might cause great numbers of river snails to be swept down swollen streams, the remains of which might be deposited in shallow coastal swamps.

The stratigraphic position of the *Scaletz* bed with reference to the Coalinga section of the Etchegoin formation is based on its relation to a "*Mulinia*" zone that underlies it. The following table shows this relation in the Buena Vista and Elk Hills and farther north on Buttonwillow and Semitropic Ridges:

*Scaletz bed and "Mulinia" zone in Buena Vista and Elk Hills and on Buttonwillow and Semitropic Ridges*

| Well                                  | Location                                                   | Depth below surface of <i>Scaletz</i> bed | Depth below surface of " <i>Mulinia</i> " zone | Stratigraphic interval between <i>Scaletz</i> bed and " <i>Mulinia</i> " zone |
|---------------------------------------|------------------------------------------------------------|-------------------------------------------|------------------------------------------------|-------------------------------------------------------------------------------|
| Ohio Oil Co., Pyramid No. 1...        | East end of Buena Vista Hills, sec. 20, T. 32 S., R. 25 E. | Feet<br>5, 180                            | Feet<br>5, 326                                 | Feet<br>146                                                                   |
| Standard Oil Co., Kern County No. 27. | East end of Elk Hills, sec. 31, T. 30 S., R. 25 E.         | (a)                                       | (a)                                            | (a)                                                                           |
| Nordon Oil Corp., Salisbury No. 1A.   | Buttonwillow Ridge, sec. 7, T. 29 S., R. 24 E.             | 4, 704                                    | 4, 791                                         | 87                                                                            |
| Richfield Oil Co., Redding No. 1.     | Semitropic Ridge, sec. 36, T. 27 S., R. 23 E.              | 4, 743                                    | 4, 656                                         | (b)                                                                           |
| Shell Oil Co., Williams No. 1....     | Semitropic Ridge, sec. 17, T. 27 S., R. 23 E.              | 4, 706                                    | 4, 785                                         | 79                                                                            |

<sup>a</sup> Figures not available.

<sup>b</sup> In this well a "*Mulinia*" zone lies above the *Scaletz* bed. Another "*Mulinia*" zone is recorded at a depth of 4,722 feet.

<sup>46</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 88-162, 1920.



This "*Mulinia*" zone is regarded as the upper "*Mulinia*" zone of the Coalinga region, which, according to Arnold and Anderson,<sup>47</sup> lies 2,000 to 2,700 feet below the top of the Etchegoin formation. In the Kettleman Hills a bed that carries fresh-water fossils in its upper part lies about 60 feet above the highest "*Mulinia*"-bearing bed of the upper "*Mulinia*" zone. If the "*Mulinia*" zone in the wells in the southwestern part of San Joaquin Valley actually corresponds to the upper "*Mulinia*" zone, this fresh-water bed lies in the fresh-water zone of which the *Scalez* bed is a member, but so far no specimens of *Scalez* and no *Viviparus*-like shells have been found at this horizon—nor at any other horizon—near Coalinga. It is improbable, however, that the thickness of beds between the upper "*Mulinia*" zone and the top of the Etchegoin formation remains constant between Coalinga and the south end of San Joaquin Valley.

Current opinions as to the age of the Etchegoin formation are based on evidence furnished by the remains of fossil horses found in the Coalinga region, as described by Merriam in the papers already cited. The *Hipparion* zone, which lies in the Jacalitos formation, underlying the Etchegoin formation, is regarded as lower Pliocene, the *Plihippus coalingensis* zone of the Etchegoin as early middle Pliocene, and the "*Plihippus*" *proversus* zone of the upper Etchegoin as late middle Pliocene. "*Plihippus*" *proversus* was recognized by Merriam as an advanced species and is now placed in the genus *Plesippus*,<sup>48</sup> which is intermediate between *Plihippus* and the modern genus *Equus*.

#### MARICOPA SHALE

The Maricopa shale unconformably underlies the Etchegoin formation along the mountain front. It is the "brown shale" of drillers and is regarded by many as the source of the oil in the fields along the west and south sides of the valley. On the flanks and crest of the Temblor Range it is divided, as mapped and described by Pack,<sup>49</sup> into a lower part consisting principally of mud shales, siliceous shale, and diatomite and an upper part comprising chiefly soft, punky diatomite and coarse detrital deposits. Many of the beds carry diatoms, radiolarians, and sponge spicules, and others carry foraminifers. At its type locality near Maricopa the thickness of the Maricopa shale is 4,800 feet, but the maximum thickness at the south end of the valley is undoubtedly considerably greater.

As a result of the recovery of core samples during recent years a mass of data has accumulated on the stratigraphic relations of the

<sup>47</sup> Arnold, Ralph, and Anderson, Robert, Geology and oil resources of the Coalinga district, Calif.: U. S. Geol. Survey Bull. 398, pp. 118–124, 1910.

<sup>48</sup> Matthew, W. D., A new link in the ancestry of the horse: Am. Mus. Novitates, No. 131, 2 pp., 1924.

<sup>49</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 35–42, 1920.

Etchegoin formation and Maricopa shale in the Sunset-Midway field. Many of the oil operators prefer to use the terms "Monterey shale" and "Santa Margarita(?) formation," as used by Arnold and Johnson<sup>50</sup> in an early report, for the beds lumped by Pack as Maricopa shale. The coarse detrital beds in the Santa Margarita (?) formation indicate a pronounced change of some kind, presumably an elevation of the adjoining mountains. The sea began to withdraw as these beds were laid down. There is some evidence that during Santa Margarita(?) time minor folds had begun to form. According to the evidence afforded by cores, the coarse detrital material does not extend out into the valley. After these coarse beds were laid down the deposits were folded and elevated above sea level, the result in the Midway district being a monocline that has a general trend of N. 47° W. After a period of erosion, during which at places along the present foothills and the Midway Valley deep stream channels were cut, the Etchegoin sea began to transgress this surface. The Etchegoin deposits constitute an overlapping series, successively younger beds reaching a progressively higher altitude on the slope of the monocline.<sup>51</sup> The stratigraphic interval between a recognizable bed in the Etchegoin formation and the top of the "brown shale" remains fairly uniform along a trend of N. 47° W., corresponding to the trend of the surface on which the Etchegoin formation was laid down, except at the places where the stream channels were cut and where the Etchegoin was deposited on folds, but the interval becomes progressively greater northeastward down the slope of the monocline.

## STRUCTURE

### GENERAL FEATURES

Structurally the Elk Hills are a broad, flat-topped arch with steeper dips along the edge than farther up the flanks. At places near the edge the surface beds, at least, are crumpled into narrow flat-topped anticlines. The structure of the oil-bearing beds is known with certainty only for the eastern field. There it is similar to the structure of the surface beds but the dips are considerably steeper.

### RELATIONS TO REGIONAL STRUCTURE

In the region west and northwest of the Elk Hills the mountain ranges constituting the Coast Ranges and the valleys between them lie a little athwart the main mountain belt, and the outer ranges

<sup>50</sup> Arnold, Ralph, and Johnson, H. R., Preliminary report on the McKittrick-Sunset oil region: U. S. Geol. Survey Bull. 406, pp. 55-74, 1910.

<sup>51</sup> See Farnsworth, H. R., The sedimentation of the Sunset oil field and the extension of the Thirty-five anticline: Oil Bulletin, vol. 13, No. 11, pp. 1133-1139, 5 figs., 1927.

emerge from the general mass along the coast and along San Joaquin Valley. The Diablo Range forms the western border of San Joaquin Valley for a long distance but finally plunges southeastward and disappears in the foothills north and northeast of Antelope Valley. Farther south the Temblor Range takes its place. Part of the Temblor Range merges into the eastward-trending San Emigdio Mountains, but most of it plunges into the valley in the area that extends southward from the Elk Hills. In the Temblor Range itself

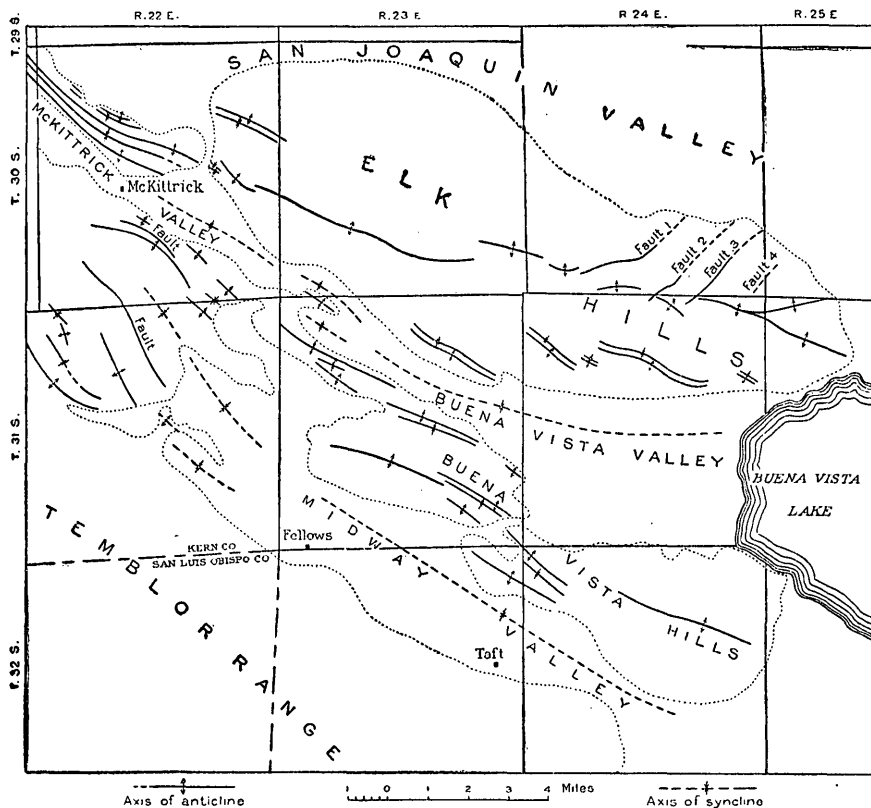


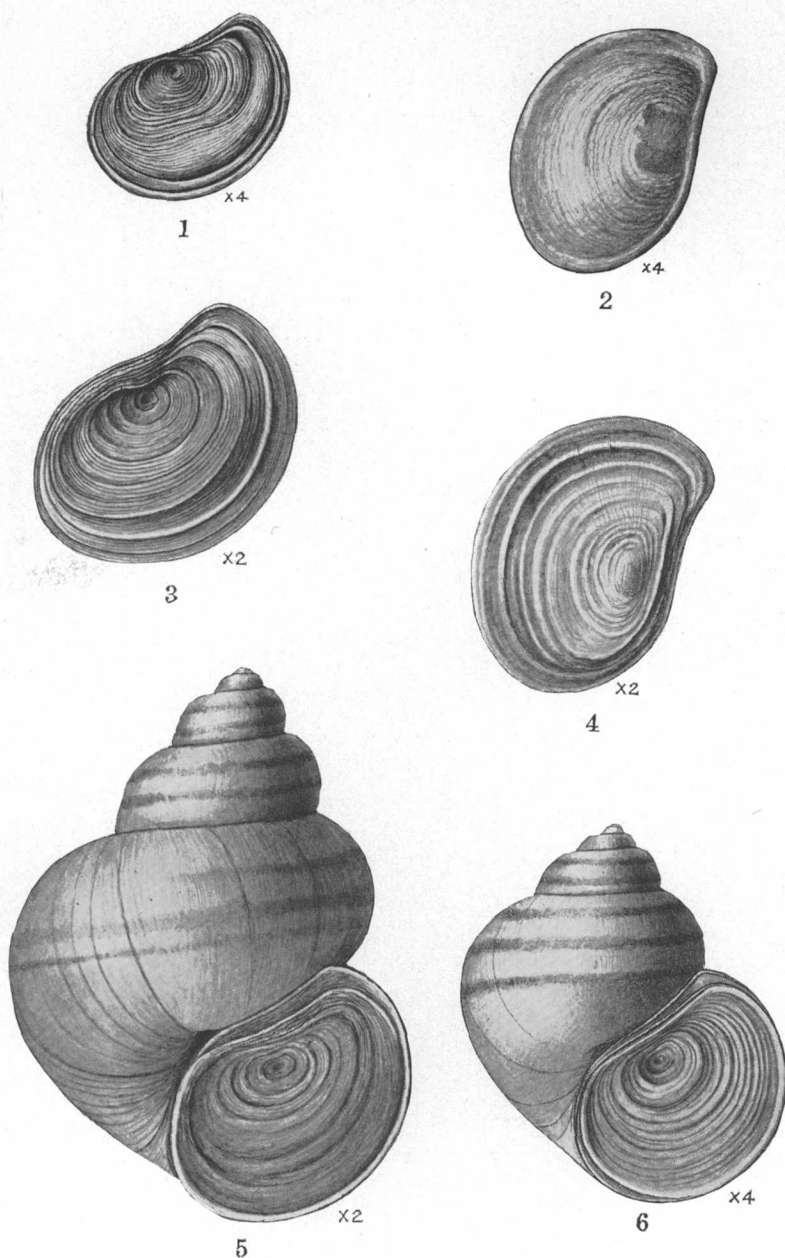
FIGURE 3.—Sketch map showing folds in foothills of Temblor Range adjoining Elk Hills. (Adapted from Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pl. 2, 1920.) Folds on slope of main range not shown. Boundary between folded Tertiary and Pleistocene beds and flat-lying alluvium shown by dotted line

the folds are closely compressed; in the foothills they are more open. In the outer part of the range individual folds trend obliquely across it and emerge into the valley, duplicating on a small scale the arrangement of the main ranges. The broad, open folds of the Elk Hills lie at the east end and along the north edge of the plunging foothills of the Temblor Range. At the west end of the Elk Hills and farther west the folds in the foothills are narrower and more steeply folded, and the foothills themselves are correspondingly narrower. (See fig. 3.)

## SURFACE STRUCTURE

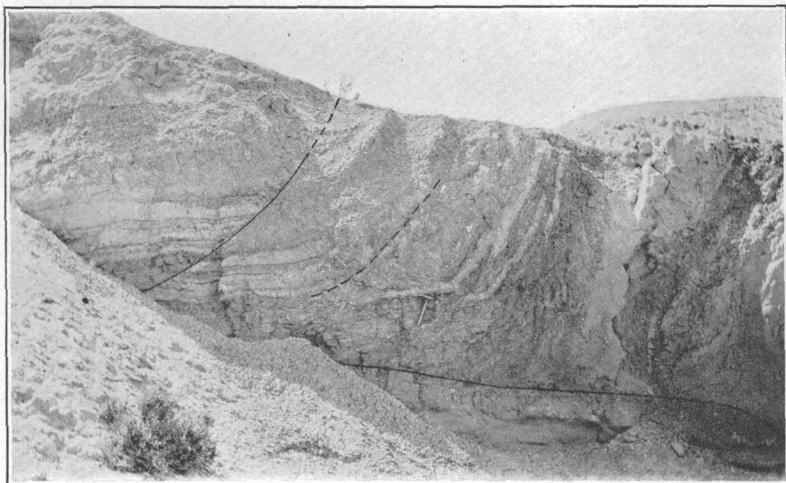
The structure of the surface beds is shown on Plate 1. Contours with an interval of 25 feet are shown over the entire area, except where the dip is unusually steep, though the degree of accuracy attained in the mapping perhaps fails to warrant this interval at places; an error in location involving one topographic contour line would throw the structure lines off by almost one contour interval, and the minor sinuosities may be only approximate, except in areas where one mappable bed is exposed over a large area. Good exposures over extensive areas indicate the probability that in regions where exposures are poor more than one lenticular mudstone was mapped as the same bed. Nevertheless there is every reason to believe that limestones A and B and the first and third mudstones above the base of the upper part of the Tulare formation are continuous over large areas. Inasmuch as these beds were mapped along the crest and along most of the north slope, it is in these areas that presumably the greatest degree of accuracy was attained.

According to Plate 1, the Elk Hills consist of two main anticlinal folds arranged en échelon. Both folds are broad-topped and have steeper dips along the edge, particularly along the south edge. The western fold is far simpler than the eastern one, but near the west end of the hills it is replaced by narrow anticlines characteristic of the narrow belt of foothills farther west; in fact, one of these anticlines is the plunging end of a fold that extends across the stream gap at the west end of the hills. The crest of the eastern anticline consists of a number of domes or terracelike steps that send anticlinal noses down the north slope, between which lie faults. These faults, which have no topographic expression whatever, are mapped on the basis of the distribution of the buff mudstone at the base of the upper part of the Tulare formation; the principal ones are designated by numbers, from west to east. (See pls. 1, 12, and 13.) Along these faults the west side is dropped and the buff mudstone lies against the olive-gray mudstones of the lower part of the formation. This relation is well shown along fault 1 on the main ridge in the northern part of sec. 33, T. 30 S., R. 24 E., and on three adjoining spurs to the east. Along fault 2 it is clearly seen on the spur northeast of well No. 12, in the Belridge lease, in section 34. It also is well exposed along fault 3 immediately east of wells Nos. 54 and 113, in section 35. Along fault 4 it was seen at only one place, in the spur southeast of well No. 22, in sec. 31, T. 30 S., R. 25 E. Where buff mudstones are faulted against similar beds, as near the edge of the hills, the faults generally can not be seen, and their location is attempted by carrying in mapping from both sides, a procedure which is none too certain. Likewise the faults can not be

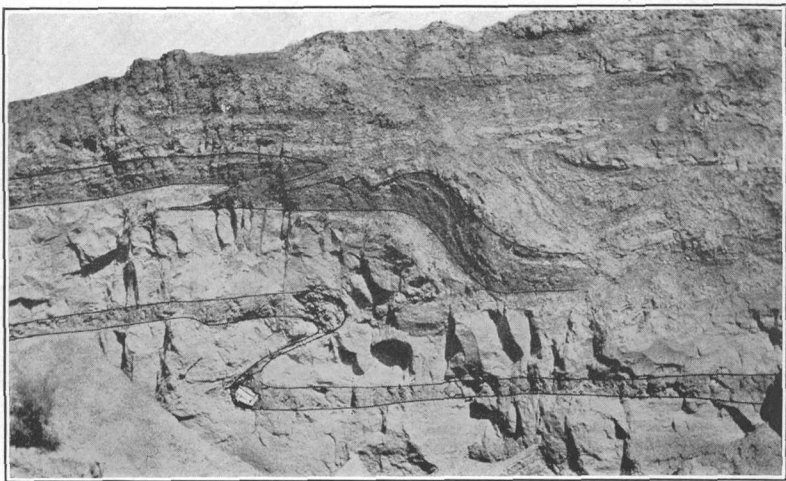


SCALEZ PETROLIA AND SHELLS AND OPERCULA OF LIVING SPECIES OF  
VIVIPARUS

1. *Scalez petrolia* Hanna and Gaylord. Exterior. Pacific Oil Co.'s well No. 103, sec. 35, T. 30 S., R. 24 E.; depth, 2,763 feet; U. S. G. S. station 1/921. U. S. Nat. Mus. catalogue No. 353687. The growth lines are irregular, owing to some accident during growth.
2. *Scalez petrolia* Hanna and Gaylord. Interior, same locality and depth. U. S. Nat. Mus. catalogue No. 353688.
- 3, 4. *Viviparus intertextus* (Say). Exterior (3) and interior (4) of operculum of adult shell. Alexandria, La. U. S. Nat. Mus. catalogue No. 106230.
- 5, 6. *Viviparus conlectoides* (Binney). Adult (5) and young (6) shells with opercula in attached position. Erie Canal, Mohawk, N. Y. U. S. Nat. Mus. catalogue No. 27741.



A



B

SMALL THRUST FAULTS AND OVERTURNED FOLDS ON NORTH SLOPE OF ELK HILLS ALONG STREAM IN SEC. 16, T. 30 S., R. 23 E.

A, View on west bank of stream; B, view on east bank about 500 feet farther upstream.

seen where olive-gray mudstones are faulted against olive-gray mudstones, and this may account for the failure to trace fault 4 toward the crest or to the edge of the hills. The presence of several faults in the oil-bearing beds of the eastern field was known long before the surface faults were discovered. They have essentially the same trend as the surface faults, and along them the west side is dropped, as at the surface. It is safe to assume, therefore, that the surface faults are the same as the faults that displace the oil-bearing beds. Fault 1, which at the surface has the greatest maximum displacement (160 feet), lies at the western edge of the developed area. Faults 2, 3, and 4, which are within the developed area, are normal faults and dip toward the northwest. The relation between them at the surface and at the depth of the oil-bearing beds is summarized as follows:

*Dip of fault plane and maximum displacement along faults on north slope of eastern part of Elk Hills*

|                                                         | 2   | 3   | 4  |
|---------------------------------------------------------|-----|-----|----|
| Dip.....degrees.....                                    | 66  | 60  | 55 |
| Maximum displacement at <i>Scales</i> bed.....feet..... | 215 | 220 | 65 |
| Maximum displacement at surface.....do.....             | 105 | 115 | 50 |

According to these data, the relative magnitude of displacement is the same at the surface and at the *Scales* bed, and the dip of the fault planes is progressively steeper from east to west. Fault 5 (see pls. 12 and 13), which has a maximum displacement of 35 feet in the oil-bearing beds, was not recognized at the surface, nor were any of the other minor faults that are shown on Plate 13. The incentive to search for the faults at the surface was furnished by the knowledge that faults of considerable displacement affect the oil-bearing beds, and it is possible that other surface faults, outside the developed areas, escaped unrecognized.

The short narrow anticlines are the most striking structural feature. They fall into two groups—those at the west end that form the main crest of the hills and those along or near the edge. The two folds of the first group are not so narrow nor so steeply folded as most of those of the second group. They apparently are to be correlated with the main broad folds. Of the anticlines along or near the edge, five lie along the south slope and one on the north slope. Their appearance depends on the depth to which they have been eroded. The one on the north slope at the west end of the hills is the least eroded of all, and consequently its form is faithfully shown by the topography; though very narrow, it is a flat-topped

asymmetric arch with steeper dips on the north limb. Those on the south slope are progressively more deeply eroded from west to east. The westernmost one shows a high degree of topographic expression (see pls. 5 and 6); in its western part the crest is broad and clearly seen, but in the eastern part, which is eroded 100 to 200 feet deeper stratigraphically, the crest is much narrower and less distinct, though it is represented as broad-topped at the horizon of the datum bed; this anticline also is slightly asymmetric and for a short distance has steeper dips on the south limb, though these are disguised by the more prominent dip slope on the north limb. The second anticline from the west is apparently steeper on the north limb, where dip slopes of  $60^{\circ}$  to  $70^{\circ}$  constitute its most conspicuous topographic form; the exposures on the south limb, however, are unsatisfactory. The crest is indistinct except at the plunging ends but is unmistakably narrow. The short third anticline also seems to be steeper on the north limb, where the beds dip  $30^{\circ}$  to  $40^{\circ}$ , but on the south limb the steepest dip that was seen is under  $20^{\circ}$ . The long sinuous anticline next to the east is imperfectly represented topographically; at least the eastern part, where dips of  $75^{\circ}$  to  $90^{\circ}$  extend close to the crest, has a steeper south limb; the narrow crushed crest is well exposed in the stream cut in the western part of sec. 9, T. 31 S., R. 24 E., and at other places along the crest small patches of rock of distinct color extend for short distances and abruptly strike into other kinds of rock, indicating that the crest is badly crushed. The short easternmost anticline has the most obscure topographic form, but it forms a low ridge. Dips as high as  $40^{\circ}$  are visible on the south limb. The north limb, unlike the north limb of the other folds, is very indistinct.

From the preceding account it is apparent that these narrow anticlines have broad crests where they are slightly eroded and narrow crests where they are more deeply eroded—features that support the opinion expressed in earlier reports that they are shallow and therefore need not be considered so far as oil prospects are concerned. The representation of the more deeply eroded anticlines on Plate 1 is an attempt to reconstruct them at the horizon of the datum bed and is based on the form of the less eroded ones. The contours show them as having broader crests and more gently dipping limbs than can be seen on the ground.

That these folds are not due to slumping on a large scale is indicated by their height relative to the height of the main folds, as well as by the gentle slope on which they lie and by their absence on the steeper north slope, except at the west end, where the slope is gentle. That slumping has taken place on a smaller scale is indicated by the curious little thrust faults and overturned folds along



the stream in sec. 16, T. 30 S., R. 23 E. (see pl. 11), for which no other reasonable explanation is apparent. The position of the westernmost fold along the south edge of the hills opposite a similar anticline along the north edge of the Buena Vista Hills (see fig. 3) lends support to the suggestion, brought forward by H. W. Hoots, that these two folds facing each other across the Buena Vista syncline are drag folds due to slipping and buckling as the Elk and Buena Vista Hills were arched up and the syncline between them was deepened. The four other folds on the south slope have no counterpart, however, in the Buena Vista Hills, and the one at the northwest edge, which according to topographic form is the youngest of all, faces the broad San Joaquin Valley. It is of such recent date that there could not be a completely buried fold of the same age out in the valley. The main broad folds and also the minor ones are probably due to rotational stress set up by horizontal movements in the basement rocks. The area of crowded minor folds that extends eastward into the Elk Hills lies in front of the McKittrick thrusts.

## STRUCTURE OF OIL-BEARING BEDS

### EASTERN FIELD

The structure of the oil-bearing beds in the eastern field is shown on Plates 12 and 13.

The contours on Plate 12, based on data from outlying wells and from wells in the producing field, are drawn on the top of the *Scales* bed. In the area covered by this map there are 106 wells from which *Scales* has been reported. Of these records 11 were considered unreliable. The older wells were drilled before the *Scales* bed was recognized, and its probable depth in these wells was determined by an interpretation of logs in the light of *Scales* records from near-by wells.

The contours on Plate 13 are drawn on the top of the *Scales* oil zone, the main oil zone of the eastern field, which lies from 0 to 35 feet, or rarely a little more, below the *Scales* bed. In assembling the data for this map the log and core records of formation, the histories of mechanical operations during drilling, and the records of production and of repair work were interpreted.

It will be seen that the two maps are somewhat different in details, particularly with reference to minor sinuosities and minor faults. Inasmuch as the maps represent different horizons and the differences between them are largely a matter of interpretation, no attempt has been made to reconcile them. If *Scales* records were available for the entire area, the top of the *Scales* bed undoubtedly would be a more precise datum plane than the top of the *Scales* oil zone.

Aside from minor features the structure of the surface beds and of the oil-bearing beds is similar in general plan, the principal difference being that the dip is much greater in the oil-bearing beds than at the surface. This relation is clearly shown by the following measurements:

*Comparison of dip in surface beds and in Scalez bed in eastern field*

| Location of section                                                                                                                                                    | Length of section | Difference in altitude |               |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|------------------------|---------------|
|                                                                                                                                                                        |                   | Surface beds           | Scalez bed    |
| From U. S. Navy Pan American No. 2, NE. $\frac{1}{4}$ sec. 1, T. 31 S., R. 23 E., to Pan American No. 4-B, NW. $\frac{1}{4}$ sec. 6, T. 31 S., R. 25 E.-----           | Miles<br>6.52     | Feet<br>505            | Feet<br>1,502 |
| From U. S. Navy Pan American No. 2, NE. $\frac{1}{4}$ sec. 1, T. 31 S., R. 23 E., to McNeil-Kaufman No. 1, SW. $\frac{1}{4}$ sec. 22, T. 30 S., R. 24 E.-----          | 3.82              | 710                    | 2,036         |
| From U. S. Navy Pan American No. 3-K, NE. $\frac{1}{4}$ sec. 3, T. 31 S., R. 24 E., to Petroleum Producers No. 1, NW. $\frac{1}{4}$ sec. 14, T. 31 S., R. 24 E.-----   | 2.10              | 280                    | 1,854         |
| From U. S. Navy Elk Hills Petroleum No. 17, SE. $\frac{1}{4}$ sec. 34, T. 30 S., R. 24 E., to Associated No. 52, SE. $\frac{1}{4}$ sec. 28, T. 30 S., R. 24 E.-----    | 1.72              | 460                    | 855           |
| From U. S. Navy Elk Hills Petroleum No. 17, SE. $\frac{1}{4}$ sec. 34, T. 30 S., R. 24 E., to McNeil-Kaufman No. 1, SW. $\frac{1}{4}$ sec. 22, T. 30 S., R. 24 E.----- | 2.06              | 635                    | 1,382         |

\* This figure is based on an estimate for the depth of the Scalez bed in Associated No. 52.

The difference in dip is shown also in sections *A-A'* and *B-B'*, Plate 12. The marked difference in dip and in the thickness of the beds on the crest and flanks is attributed to the gradual growth of the folds represented by the hills during Etchegoin and Tulare time. This conception implies a series of minor overlaps and unconformities in the Etchegoin and Tulare.

The representation of fault 1 on Plate 12 is based on the assumption that it is of the same character as the other faults that appear on the surface. Development has not yet reached the area where it is expected that this fault will be found in the oil-bearing beds.

#### CENTRAL FIELD

Scalez records are available for only one well in the central field (No. 2, in sec. 1, T. 31 S., R. 23 E.), which lies at the south edge of the producing area. The lack of additional Scalez data, the great number and thickness of the oil-bearing beds, and the absence of any marked lithologic datum planes make an attempt to interpret the logs almost hopeless. An early subsurface structure map of this area was published by Thoms and Smith,<sup>52</sup> and a recent one by Pemberton.<sup>53</sup>

<sup>52</sup> Thoms, C. C., and Smith, F. M., Notes on Elk Hills oil field: California State Min. Bur. Summary Operations California Oil Fields, vol. 7, No. 1, pp. 7-19, 4 pls., 2 figs., 1921.

<sup>53</sup> Pemberton, J. R., Elk Hills, Kern County, California: Structure of typical American oil fields, vol. 2, fig. 5 (p. 52), 1929.

## OIL AND GAS

## HISTORY OF DEVELOPMENT

During the early development of the Sunset-Midway field from 1890 to 1900, prospecting was confined to the mountain front, where asphalt deposits and seeps of heavy oil afforded the incentive for drilling.<sup>54</sup> The ruinous drop in the price of crude oil in 1903, due to the flood of oil from the Kern River field, discouraged drilling, but operations were resumed in 1907 when the price rose. The departmental order of September 27, 1909,<sup>55</sup> withdrawing from all forms of entry the public lands in the Elk Hills and other parts of the area retarded development at a time when overproduction threatened. By 1909 prospecting had left the mountain front and reached the Buena Vista Hills, where the first producing well was completed in 1910.

It has not been possible to verify a report<sup>56</sup> that a well was drilled in 1901 in the Elk Hills in sec. 2, T. 31 S., R. 24 E., to a depth of 600 feet and that it obtained a small quantity of oil. The first wells in the Elk Hills of which there is definite record were drilled in 1910-11, when development spread northward from the Buena Vista Hills. More than 20 wells were started in 1910, and several others in 1911. Only a few of these wells were drilled deep enough to test the oil possibilities, and only the three noted below obtained oil.

*Early oil-producing wells in Elk Hills*

|                                                    | Reported<br>daily pro-<br>duction<br>of oil | Gravity           | Depth       | Date              |
|----------------------------------------------------|---------------------------------------------|-------------------|-------------|-------------------|
|                                                    | <i>Barrels</i>                              | <i>° Baumé</i>    | <i>Feet</i> |                   |
| Associated No. 1, sec. 26, T. 30 S., R. 23 E.----- | 75                                          | 30                | 4,030       | March, 1911.      |
| Associated No. 1, sec. 30, T. 30 S., R. 24 E.----- | 350                                         | 26.4              | 3,836       | January, 1912.    |
| Associated No. 3, sec. 24, T. 30 S., R. 23 E.----- | <sup>b</sup> 20-800                         | <sup>c</sup> 21.8 | 3,887       | April-June, 1912. |

<sup>a</sup> Original depth, 3,548 feet.

<sup>b</sup> 800 or 900 barrels recorded as maximum yield during period when well was flowing.

<sup>c</sup> As recorded on June 8, 1912.

During the suit brought by the Government to clear title to the lands on which these wells were drilled, which were within the boundary of Naval Petroleum Reserve No. 1, created by Executive order of September 2, 1912, the Associated Oil Co. testified to a total production of 9,941 barrels of oil from the three wells.<sup>57</sup> Operations at these wells and the others drilled during this early period were

<sup>54</sup> See Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 63-66, 1920.

<sup>55</sup> See U. S. Geol. Survey Bull. 623, pp. 135-149, 1916.

<sup>56</sup> Federal Reporter, vol. 249, p. 788, 1918.

<sup>57</sup> U. S. Geol. Survey Prof. Paper 116, p. 164, 1920.

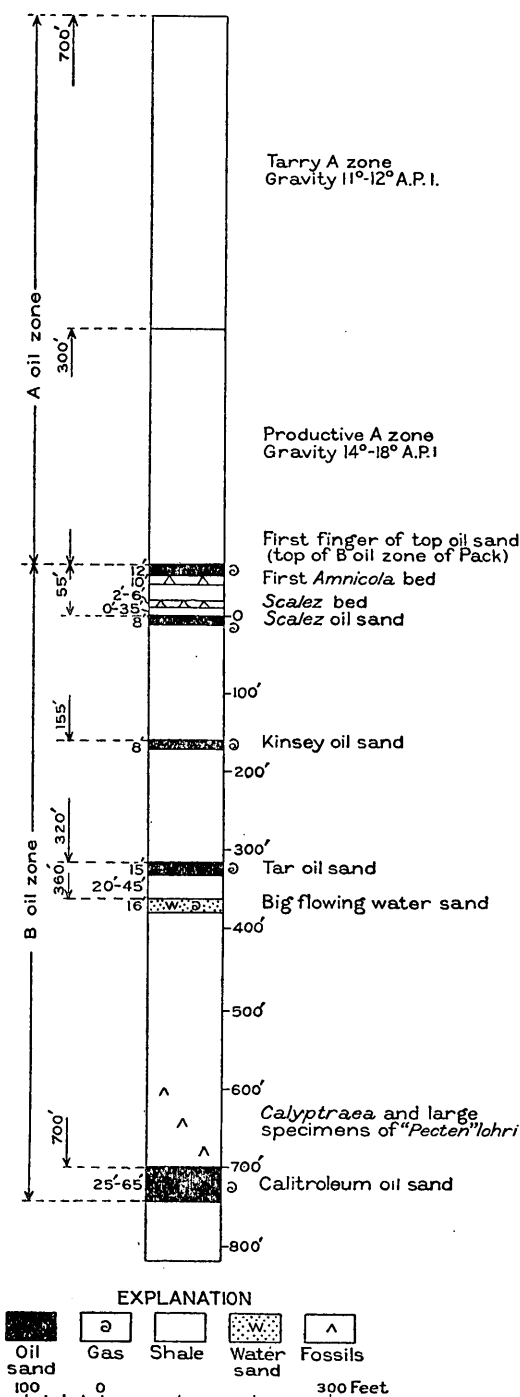


FIGURE 4.—Distinctive beds in upper part of Etchegoin formation of Midway field. Single figures represent averages

soon suspended. If the title of the lands had not been in dispute, there is little doubt that the Elk Hills would have developed as a field before the end of 1912, and Associated No. 1, in sec. 26, T. 30 S., R. 23 E., would be known as the discovery well. When the Pan American Petroleum Co. leased the reserve in 1922 this well was repaired and put into condition to go on production as a gas well.

Development again started in 1918, after the Standard Oil Co. had acquired title to a part of a school section (sec. 36, T. 30 S., R. 23 E.) lying in the center of the hills. Hay No. 1 was completed in January, 1919, with an average daily production for the first month of about 225 barrels of oil having a gravity of 37.2° Baumé. This well is generally referred to as the discovery well. Development proceeded in section 36 and adjoining sections constituting the central field. The discovery of the dry-gas zone in this field is described on page 53.

Drilling in the eastern field was started in 1919 by the Standard Oil Co., which had acquired another school section (sec. 36, T. 30 S., R. 24 E.), and

early in 1920 brought in several wells, each of which had an initial daily production of several thousand barrels. On account of the policy of the Government to hold the public lands in the reserve for the purpose for which they were set aside—a policy that has been strengthened since the repudiation of the wholesale leasing in 1922—and on account of the liberal attitude of the holders of patented land within the reserve, development has been confined to small areas within the two fields and has been almost at a standstill since 1926. Indeed, in the central field, where the yields of oil have generally been small, almost half the wells are shut in. Despite this

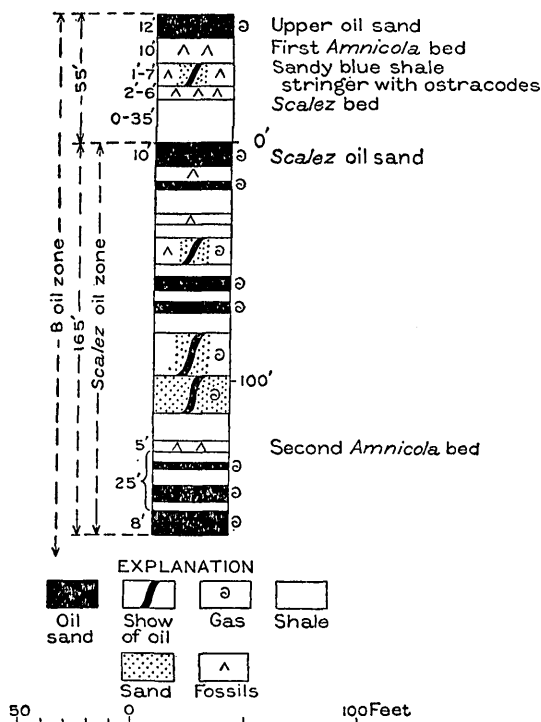


FIGURE 5.—Distinctive beds in upper part of Etchegoin formation of eastern field, Elk Hills. Single figures represent averages

policy of holding down drilling, more than 400 wells had been drilled in the Elk Hills up to the end of 1928.

## OCCURRENCE

### GENERAL FEATURES

The productive oil-bearing beds and also the dry-gas zone of the Elk Hills are found in the upper part of the Etchegoin formation. The distinctive beds in the upper part of the Etchegoin formation of the Midway field and in the eastern field of the Elk Hills are shown in the following table and in Figures 4 and 5. These beds are used as stratigraphic "markers" by the oil operators.

## Distinctive beds in upper part of Etchegoin formation of Midway field and in eastern field, Elk Hills

| Midway field                                                 |                   |                                                                                      | Eastern field, Elk Hills                                              |                   |                                                                                | Characteristic features                                                                                                                                                                                            |
|--------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bed                                                          | Thick-<br>ness    | Strati-<br>graphic<br>interval<br>between<br>top of bed<br>and <i>Scaletz</i><br>bed | Bed                                                                   | Thick-<br>ness    | Stratigraphic<br>interval be-<br>tween top of<br>bed and <i>Scaletz</i><br>bed |                                                                                                                                                                                                                    |
|                                                              | Feet <sup>a</sup> | Feet <sup>a</sup>                                                                    |                                                                       | Feet <sup>a</sup> | Feet <sup>a</sup>                                                              |                                                                                                                                                                                                                    |
| First finger of top oil sand (top<br>of B oil zone of Pack). | 12                | +32                                                                                  | Upper oil sand.....                                                   | 12                | +32                                                                            | Persistent oil-bearing bed.                                                                                                                                                                                        |
| First <i>Amnitcola</i> bed.....                              | 10                | +20                                                                                  | First <i>Amnitcola</i> bed.....                                       | 10                | +20                                                                            | Abundance of fresh-water gastropods ( <i>Amnitcola</i> ). Large fresh-<br>water mussels ( <i>Anodonta?</i> ) in upper part.                                                                                        |
| <i>Scaletz</i> bed.....                                      | 2-6               | 0                                                                                    | Sandy blue shale stringer with<br>ostracodes.....                     | 1-7               | +3                                                                             | Abundance of smooth fresh-water ostracodes. Shows colors of oil.                                                                                                                                                   |
| <i>Scaletz</i> oil sand.....                                 | 8                 | 0 to -35                                                                             | <i>Scaletz</i> oil sand (top of lower or<br><i>Scaletz</i> oil zone). | 10                | 0 to -35                                                                       | Brittle greenish-brown shale of uniform color, texture, and thick-<br>ness carrying great number of calcareous gastropod opercula<br>( <i>Scaletz petrolia</i> ), but hardly any other fossils.                    |
| Kinsey oil sand.....                                         | 8                 | -180                                                                                 | Second <i>Amnitcola</i> bed.....                                      | 5                 | -100 to -155                                                                   | Persistent saturated oil sand lying immediately below <i>Scaletz</i> bed<br>or separated from it by interval of as much as 35 feet.                                                                                |
| Tar oil sand.....                                            | 15                | -344                                                                                 | Base of lower or <i>Scaletz</i> oil zone.....                         | 8                 | -180                                                                           | Blue sandy shale carrying abundant <i>Amnitcola</i> and other fresh-<br>water fossils.                                                                                                                             |
| Big flowing water sand.....                                  | 16                | -384                                                                                 |                                                                       |                   |                                                                                | Persistent saturated oil sand.                                                                                                                                                                                     |
| Calitroleum oil sand.....                                    | 25-45             | -720                                                                                 |                                                                       |                   |                                                                                | Gravity of oil 14° to 17° A. P. I. or about 4° lower than that of any<br>other oil from beds in Etchegoin below "first finger of top oil."                                                                         |
|                                                              |                   |                                                                                      |                                                                       |                   |                                                                                | On account of low gravity and associated gas, oil generally shows<br>on ditch when drilling through it.                                                                                                            |
|                                                              |                   |                                                                                      |                                                                       |                   |                                                                                | Carries water under particularly high head. Generally flows to<br>surface when bed is left open in a well. Oil and gas shows fre-<br>quent. These shows and flood of salt water make it a striking<br>"marker."    |
|                                                              |                   |                                                                                      |                                                                       |                   |                                                                                | Thickest productive sand in Etchegoin. Large scallops (" <i>Pecten</i> "<br><i>lohr</i> ) and slipper-limpets ( <i>Calyptraea</i> ) generally found in over-<br>lying beds through an interval of almost 100 feet. |

<sup>a</sup> These figures are averages except where extremes are given.

In addition to the beds tabulated, the productive A zone and the tarry A zone, lying immediately above the B zone in the Midway field<sup>58</sup> may be recognized by the gravity of the oil that they carry. (See fig. 4.) Even if they are not productive the heavy oil in the tarry A zone generally gives the uppermost oil shows in wells that are drilled through rocks of this age.

#### EASTERN FIELD

In the eastern field most of the oil produced has come from beds lying below the *Scaletz* bed, constituting the lower or *Scaletz* oil zone. As shown in Figure 5, this zone has a total average thickness of 165 feet. It consists of several oil sands separated by sandy "shales" that carry shows of oil and by barren "shales." Wells are drilled to varying depths within this zone, the depth depending on the horizon where good pay is obtained or on the producing depth of offset wells. Many wells have produced from a sand lying above the *Scaletz* oil zone, as will be brought out in the discussion of the fluids in the sands and their movements. This sand, which is called the upper oil sand, has an average thickness of 12 feet, and its top is separated from the top of the *Scaletz* oil zone by an average interval of 55 feet. It corresponds to the "first finger of top oil sand" (top of B zone) in the Midway field, and the entire productive zone in the eastern field of the Elk Hills, embracing the interval from the top of this upper oil sand to the base of the *Scaletz* oil zone, corresponds to the upper part of the B zone of the Midway field. The correlation of the productive beds in the Elk Hills with those in the Midway field is particularly interesting, inasmuch as the sub-surface contours drawn by Pack over a large part of the Midway field<sup>59</sup> are based on the top of the B zone. The manner in which the contours of this map agree with data based on core records, which are more precise than any available to Pack, is a tribute to the painstaking care with which his map was prepared.

No well that is favorably located structurally has penetrated the sands that lie below the water sands in the middle part of the B zone and that yield oil in the Midway field. These productive beds correspond to Pack's C zone, but this designation was not used by him for the same beds in Maricopa Flat.

The showings of oil recorded within an interval of as much as 1,000 feet above the productive oil-bearing beds are referred to the A zone of the Midway field. Even the productive A zone of the Midway field has failed to yield commercial quantities of oil in the

<sup>58</sup> See Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 88-162, 1920.

<sup>59</sup> Idem, pl. 3.

Elk Hills except in a small area on the crest. In the eastern field its sands are almost completely filled with water. In the central field it carries dry gas.

That "pockets" of dry gas under high pressure may be found in the Etchegoin formation is indicated by the blowing out of well Kern County No. 10, in sec. 31, T. 30 S., R. 25 E., from an undetermined horizon below the *Scaletz* oil zone.

The total average thickness of the individual productive sands is about 60 feet. They are of medium texture and relatively high porosity. Starke<sup>60</sup> reports that under laboratory test when well packed the average porosity of several samples of sands from the eastern field was found to be 24.6 per cent. Uren,<sup>61</sup> however, determined that the porosity of a clean dry sample prepared from a mixture of the sands in the upper 100 feet of the *Scaletz* oil zone, taken from U. S. Navy well Elk Hills Petroleum No. 17, in sec. 34, T. 30 S., R. 24 E., is 34.5 per cent.

#### CENTRAL FIELD

The stratigraphy of the productive beds in the central field is less definitely known, for all except a few of the wells were drilled before core drilling came into practice. It is known, however, that the *Scaletz* bed lies between the first *Amnicola* bed and the top of the *Scaletz* oil zone, as in the eastern field. Future development should afford as definite stratigraphic records as in the eastern field. Both the upper oil zone and the *Scaletz* oil zone are represented. The *Scaletz* oil zone, the top of which in Pan American well No. 2, in section 1, lies 53 feet below the *Scaletz* bed, is much thicker than in the eastern field, and this is as true of the oil-bearing beds as of the entire zone. An interval of more than 1,200 feet in well Hay No. 10 is in the productive beds, and of this fully two-thirds is recorded as showing oil. Possibly 800 to 1,000 feet of this interval lies below the *Scaletz* bed.

Above these oil-bearing beds, which correspond to the B zone of the eastern field and of the Midway field, lies the most productive dry-gas reservoir known in California. The gas zone extends through a stratigraphic interval of about 1,000 feet and roughly corresponds to the A zone of the Midway field. The base lies immediately above the top of the B oil zone and about 100 feet above the top of the *Scaletz* oil zone. The most productive part, however, is within an

<sup>60</sup> Starke, E. A., unpublished report to Rear Admiral H. H. Rousseau and J. C. Anderson, court receivers for properties in litigation in Naval Petroleum Reserve No. 1, June 9, 1924.

<sup>61</sup> Uren, L. C., Brewster, F. M., and Farnsworth, H. R., Influence of gas pressure and of gravity on production of oil from sands: U. S. Bur. Mines, unpublished report, Jan. 19, 1925.



interval of approximately 100 feet, the base of which lies about 400 feet above the base of the gas zone.

The history of development of this gas zone affords an instructive example of the manner in which gas or oil, even under high pressure, may be overlooked in drilling with rotary tools.<sup>62</sup> In 1918, when the Standard Oil Co. filed its intention to drill Hay No. 1, the State Department of Oil and Gas, having in mind the record of the Hillcrest well, which was drilled in sec. 28, T. 30 S., R. 23 E., in 1910-11 to a depth of 1,661 feet and obtained a strong flow of gas, recommended that this relatively shallow gas zone be tested. No test was made, however, and the well was put on production in the B zone. Two other wells, Hay Nos. 2 and 3, recorded shows of gas in going through the A gas zone. Thus three wells were put down to the B zone with nothing but shows of gas from the A zone. The State officials still requested that the gas zone should be tested, and the company agreed to do so with the next well (No. 5). It came in uncontrolled and later produced at a daily rate of 33,000,000 cubic feet of dry gas under a casing-head pressure of more than 400 pounds to the square inch. Hay No. 7, drilled to the same zone, blew in with an estimated daily production of 180,000,000 cubic feet. Up to the end of 1926 it had produced a total of 43,000,000,000 cubic feet.<sup>63</sup> It is one of the great gas wells of the country.

#### CHARACTER OF THE OIL AND GAS

The oil has an asphaltic base and in general features is similar to the oil from the B zone of the Sunset-Midway field, the character of which has been described by Rogers.<sup>64</sup> In the Elk Hills the initial gravity, as shown graphically on Plate 14, ranges from 12.2° to more than 45° Baumé. The initial gravity as usually recorded does not represent clean oil, as the initial fluid generally contains some water and sediment. None of the clean oil is heavier than 15.5° to 18° Baumé, depending on the date of production. The light oils are confined to the central field, where the initial gravity ranges from 21° to 45° Baumé or a little more. In the eastern field the range is from 12.2° to a little under 28°. It is apparent that in the eastern field the heaviest oil is found along the north and east edges, which are far down on the anticline. In the central field the lightest oil is found along the northeast edge of the developed area, which again is in harmony with the structure, at least in the surface beds.

<sup>62</sup> See McLaughlin, R. P., Natural gas development in the Elk Hills, Calif.: California State Min. Bur. Summary Operations California Oil Fields, May, 1919, pp. 4-8, 1 fig.

<sup>63</sup> Doyle, F. F., Oil Bulletin, vol. 13, No. 11, p. 1155, November, 1927.

<sup>64</sup> Rogers, G. S., The Sunset-Midway oil field, Calif., pt. 2, Geochemical relations of the oil, gas, and water: U. S. Geol. Survey Prof. Paper 117, pp. 9-32, 1919.

Through the kindness of F. F. Doyle, former superintendent of the northern division of the Midway Gas Co., an analysis of the dry gas from the A zone of the central field, sampled from U. S. Navy well Pan American No. 1, in sec. 25, T. 30 S., R. 23 E., in 1925, is given below.

*Analysis of dry gas from A zone, central field*

|                                         |             |
|-----------------------------------------|-------------|
| Carbon dioxide (CO <sub>2</sub> )       | 5.6         |
| Oxygen (O <sub>2</sub> )                | 0.          |
| Methane (CH <sub>4</sub> )              | 91.1        |
| Ethane (C <sub>2</sub> H <sub>6</sub> ) | 3.3         |
|                                         | <hr/> 100.0 |

As in the dry gas of the Midway field,<sup>65</sup> methane is the predominating constituent, and the percentage of ethane is low.

### PRODUCTION

The initial daily production of oil is shown graphically in Plate 14. Where available data permitted, the initial production represented is the largest daily production during the first two weeks, as a well was not considered completed until the drilling mud and water had been removed from the well and the producing sand wall. For many wells, however, the only data available gave a stated initial production, which in some of them was the production 30 days after completion. For a few wells it was necessary to use the daily average for the first recorded period of production. It is recognized that this varying method fails to give an accurate comparison of production, but it appears to be the best available. The contrast between the two fields in initial production is not so striking as that in gravity, but the average initial production is lower in the central field. The rate of depletion, however, is very much more rapid in the eastern field. The advantage in initial gas pressure that the early wells of the eastern field had is brought out on Plate 14. It is impossible, however, to make a comparison based on time alone, for the initial production depends also on the position with reference to crests and faults, on the particular sand or sands from which the initial yield was obtained, on their contents, and on mechanical factors controlled by production methods.

The following table gives the total oil production for the entire Elk Hills. The figures for 1919 and the first half of 1920 were compiled from the records of the oil companies; those from July

<sup>65</sup> See Rogers, G. S., op. cit., pp. 33-35.

1, 1920, on were taken from issues of the California State Mining Bureau Summary of Operations of California Oil Fields.

*Oil production of Elk Hills*

| Period covered        | Total amount<br>of oil pro-<br>duced | Average<br>number<br>of wells<br>producing | Total<br>number<br>of well-<br>days | Average<br>produc-<br>tion per<br>well per<br>day |
|-----------------------|--------------------------------------|--------------------------------------------|-------------------------------------|---------------------------------------------------|
|                       | <i>Barrels</i>                       |                                            |                                     | <i>Barrels</i>                                    |
| Prior to 1919.....    | 9, 941                               | (?)                                        | (?)                                 | (?)                                               |
| 1919, first half..... | 111, 644                             | 2                                          | 304                                 | 376. 2                                            |
| second half.....      | 179, 477                             | 4                                          | 710                                 | 252. 8                                            |
| 1920, first half..... | 1, 352, 407                          | 12                                         | 1, 747                              | 774. 1                                            |
| second half.....      | 6, 074, 103                          | 34                                         | 5, 221                              | 1, 162. 0                                         |
| 1921, first half..... | 10, 193, 318                         | 68                                         | 10, 386                             | 891. 4                                            |
| second half.....      | 7, 797, 144                          | 121                                        | 19, 373                             | 402. 5                                            |
| 1922, first half..... | 6, 621, 946                          | 153                                        | 23, 867                             | 277. 4                                            |
| second half.....      | 4, 982, 368                          | 117                                        | 17, 621                             | 282. 7                                            |
| 1923, first half..... | 4, 016, 230                          | 107                                        | 17, 554                             | 228. 8                                            |
| second half.....      | 4, 071, 319                          | 105                                        | 17, 260                             | 235. 8                                            |
| 1924, first half..... | 6, 324, 018                          | 216                                        | 33, 936                             | 186. 4                                            |
| second half.....      | 7, 206, 216                          | 261                                        | 44, 711                             | 161. 2                                            |
| 1925, first half..... | 6, 782, 071                          | 278                                        | 46, 546                             | 145. 7                                            |
| second half.....      | 5, 229, 126                          | 241                                        | 39, 696                             | 131. 7                                            |
| 1926, first half..... | 5, 850, 940                          | 249                                        | 41, 348                             | 141. 5                                            |
| second half.....      | 6, 291, 218                          | 255                                        | 43, 233                             | 145. 5                                            |
| 1927, first half..... | 5, 332, 365                          | 247                                        | 40, 299                             | 132. 3                                            |
| second half.....      | 4, 645, 968                          | 223                                        | 38, 209                             | 121. 6                                            |
| 1928, first half..... | 4, 342, 803                          | 226                                        | 39, 977                             | 111. 4                                            |
|                       | 97, 414, 622                         |                                            |                                     |                                                   |

Curves showing the production by months and also the number of wells and the average number of producing wells are plotted on Plate 15. On account of overproduction elsewhere in California, almost half the potential production was closed in from September, 1922, to February, 1924.

It is the usual practice to produce the gas associated with the oil in the B zone, extract the casing-head gasoline from it, and then produce only enough additional gas from the A zone of the central field to meet the requirements of the gas company. The total annual production of gas from the Elk Hills, according to data supplied by the operating companies and by the Taft mineral-leasing office of the Geological Survey, is as follows:

*Gas production of Elk Hills*

| Year      | Thousand<br>cubic feet | Year                       | Thousand<br>cubic feet |
|-----------|------------------------|----------------------------|------------------------|
| 1919..... | 2, 595, 697            | 1924.....                  | 20, 358, 235           |
| 1920..... | 14, 616, 390           | 1925.....                  | 13, 820, 104           |
| 1921..... | 20, 997, 229           | 1926 (first 6 months)..... | 6, 091, 605            |
| 1922..... | 20, 281, 956           |                            |                        |
| 1923..... | 15, 087, 542           |                            | 115, 848, 740          |

## POSSIBLE OIL AND GAS RESOURCES OF UNDEVELOPED PARTS

The crest of the eastern main fold between the eastern and central fields may be regarded as virtually proved oil land; in fact, it is so listed by the California division of oil and gas for assessment purposes. It is expected that in this area and in the central part of the hills, as in the eastern field, production will extend far down the north slope, but only a short distance down the south slope. The record of Associated No. 3, in the southern part of sec. 24, T. 30 S., R. 23 E. (see p. 47), shows that oil is to be found at least that far north. This well was completed at a depth of 3,887 feet in April, 1912. In the first 36 hours it pumped only 30 barrels of oil. Daily amounts ranging from 12 to 190 barrels were pumped from April until early in June, when it began to flow, and flowed as much as 800 or 900 barrels daily. In August, when it was shut in, it was still flowing at a daily rate of 100 barrels and also yielding 3,000,000 cubic feet of gas, even though the hole was clogged by a lost string of tools. Water is recorded at intervals during the time when it was pumped, but not while it was flowing, indicating that the source of the water was some other sand than the one yielding the strong flow of oil and gas.<sup>66</sup> This well undoubtedly penetrated the B zone, and its record holds out promise for production even farther down the north slope in the central part of the hills.

Fault 1 should protect a large area on the north slope from the edge water that is moving up the slope in the eastern field. The narrow little anticlines near the edge of the hills are apparently shallow wrinkles and are not to be regarded as significant in considering oil possibilities.

The western main anticline, which at the surface has a closure of 150 feet and is that much higher structurally than any of the domes on the eastern anticline, is virtually untouched. Here also it is expected that the crest and much of the north slope will be productive; but the edge of productive territory undoubtedly will swing southward toward the west end, and production is not looked for within a mile or two of that end, for if the relation between surface and underground dips in the eastern field is a trustworthy guide, the west end lies far down the plunge. The yield of wells on the western anticline may not be large, but their oil undoubtedly will be light, at least along the crest. The shallow Hillcrest well, almost on the very top of the western anticline, which was drilled in 1910-11 to a depth of 1,661 feet, penetrated the A gas zone. This well, early in 1918 caught fire. In 1919, in a wrecked condition, it still could

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<sup>66</sup> The history of this well is abstracted from the record given by Pack (U. S. Geol. Survey Prof. Paper 116, pp. 168-169, 1920.)

yield daily 80,000 to 100,000 cubic feet under a pressure of 510 pounds to the square inch. It was not capped until 1922. Other wells on the western anticline deep enough for consideration are the following:

*Wells drilled on western anticline, Elk Hills*

| Well                                                                               | Depth       | Date                            | Remarks                                                                                                                                                                                              |
|------------------------------------------------------------------------------------|-------------|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                    | <i>Feet</i> |                                 |                                                                                                                                                                                                      |
| Redlands No. 1, NW. $\frac{1}{4}$ sec. 30, T. 30 S., R. 23 E.                      | 2,850       | -----                           | Showings of oil at 2,720 to 2,780 feet. Drill pipe twisted off and abandoned.                                                                                                                        |
| Scottish Oil Fields (Ltd.), No. 1, SE. $\frac{1}{4}$ sec. 20, T. 30 S., R. 23 E.   | 4,005       | October, 1911 <sup>a</sup> ---- | Gas at 2,620 feet. Showings of oil and gas at 2,900 to 3,020 feet, and of gas at 3,515 to 3,585 feet. Gas escaping in 1928.                                                                          |
| Associated No. 3, SW. $\frac{1}{4}$ sec. 22, T. 30 S., R. 23 E.                    | 2,980       | August, 1911-----               | Strong flow of water and some gas at 2,690 to 2,710 feet.                                                                                                                                            |
| General Petroleum Corp., King No. 5, SE. $\frac{1}{4}$ sec. 16, T. 30 S., R. 23 E. | 3,474       | August, 1919 <sup>b</sup> ----  | Showings at the following depths: Gas, 2,760 to 2,800 feet; oil and gas, 3,255 to 3,265 feet; oil, 3,000 to 3,315 feet; gas, 3,410 feet; oil, 3,348 to 3,355 feet; oil and gas, 3,426 to 3,440 feet. |
| Potter Oil Co., Tupman No. 1, NE. $\frac{1}{4}$ sec. 16, T. 30 S., R. 23 E.        | 4,655       | February, 1921 <sup>a</sup> --  | Showings of gas at 2,835 to 2,860 and 3,528 to 3,541 feet.                                                                                                                                           |

<sup>a</sup> Completed.

<sup>b</sup> Started.

Of these wells the Redlands and Associated No. 3 are too shallow except for the A zone. The Scottish Oil Fields well apparently is deep enough to reach the B zone. It was drilled with rotary tools below 2,030 feet, and in the light of what is known about the mud-ding off of productive beds in rotary holes in new territory <sup>67</sup> the record of this well is inconclusive. The source of the gas that was escaping in 1928 is not definitely known. It is doubtful whether the General Petroleum well in section 16 is deep enough to reach the B zone, though the Potter well probably is. Although the record of one well is indecisive, it is not expected that in this part of the hills commercial production will be found so far north as the northern part of section 16.

The two wells that were drilled in the southeastern part of sec. 14, T. 30 S., R. 22 E. (Elk Hills Development Co. Nos. 1 and 2, depths 2,893 and 4,200 feet respectively) in 1924-25 obtained only showings. They are far down the plunge of the western anticline.

### POSSIBLE ULTIMATE PRODUCTION

Estimates of future production of a field that is only partly developed are at the best only well-guided guesses. To judge from the surface structure and the correlation between surface and subsurface structure in the eastern field and from the records of scattered wells in the undeveloped areas, 18,690 acres is a conservative estimate for

<sup>67</sup> For recent examples in the near-by Buena Vista Hills see Godde, H. A., and Keyes, R. L., California State Min. Bur. Summary Operations California Oil Fields, vol. 12, No. 1, p. 7, 1926.

the extent of probable oil-bearing lands in the Elk Hills. Probable future production for individual holdings in the two developed areas was determined by the methods given in the Treasury Department manual for the oil and gas industry.<sup>68</sup> The data given in this manual for the "east side, Elk Hills district,"<sup>69</sup> were used in preparing the curve of future production for the eastern field but proved to be unsatisfactory for estimating the past production of the central field. For the central field the data given for the "Buena Vista Hills"<sup>70</sup> were used with better results. From these determinations of the future production of the operating units in the two fields the average ultimate production per developed acre for each field was obtained, and a mean of these two averages was taken as the probable ultimate production of oil per acre for the entire probable oil-bearing area of the Elk Hills. The mean thus obtained is considerably below the average obtained by considering the two fields together, owing to the fact that the more productive eastern field is more extensively developed and has a larger yield to the acre. However, it is probable that this field will show an actual ultimate production far in excess of that obtained by the method outlined. The curve used for the estimate in the eastern field applies well to much of that field, but for some parts, as applied to annual production for successive years, it gives too low a future production.

Later data from the central field seem to indicate that the early production of many of the wells was below the amount that should normally have been expected. Therefore the factor used in estimating the ultimate production of the entire area is considered conservative.

On the basis of the data outlined, it is estimated that the ultimate production of oil recoverable by methods now in use in this area is 400,000,000 barrels for the entire Elk Hills. This amount could be increased by improved methods of extraction, unless the oil sands are damaged by improper development.

## WATERS OF THE EASTERN FIELD AND THEIR MOVEMENTS

### GENERAL FEATURES

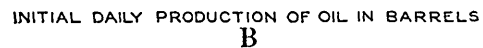
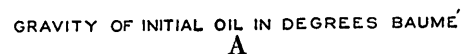
On account of the absence of edge waters in the central field and the incomplete development there, the study of the waters was restricted to the eastern field. The drilling histories, formation, production, and subsequent repair records of the wells in the eastern

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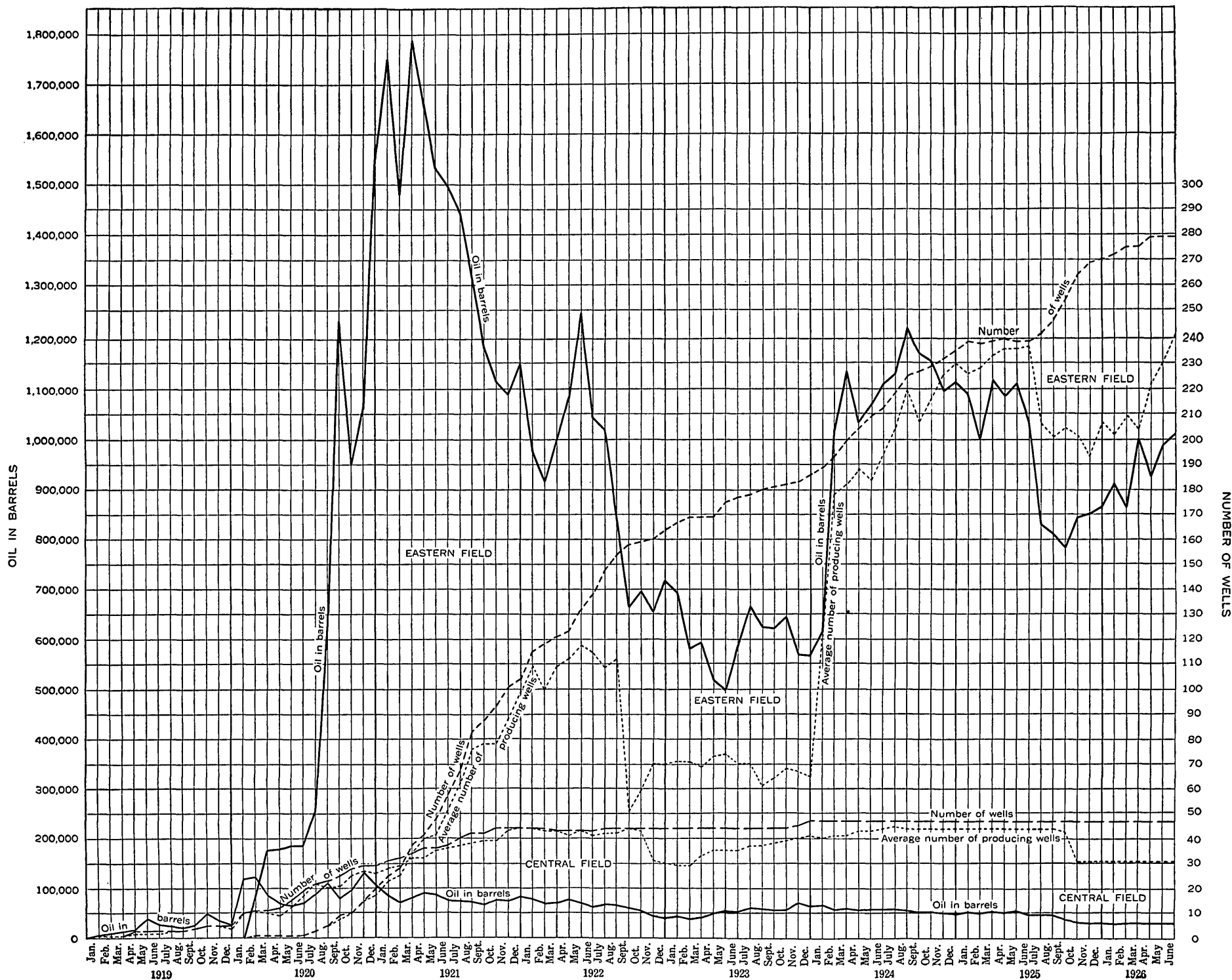
<sup>68</sup> Treasury Dept., Bur. Internal Revenue, Manual for the oil and gas industry under the revenue act of 1918, revised August, 1921.

<sup>69</sup> Idem, p. 171.

<sup>70</sup> Idem, p. 167.

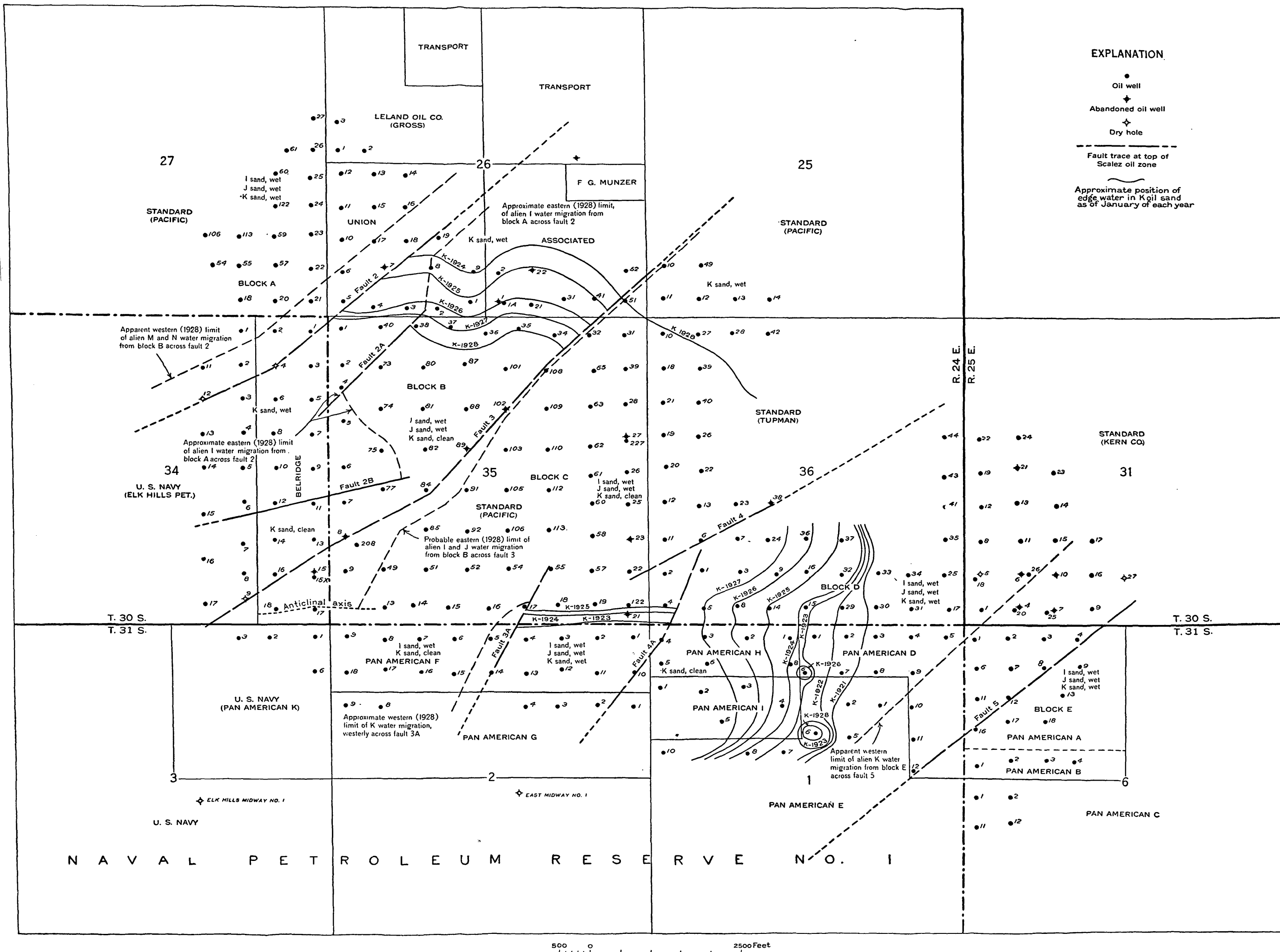


MAP SHOWING GRAVITY OF INITIAL OIL AND INITIAL DAILY PRODUCTION OF OIL, ELK HILLS

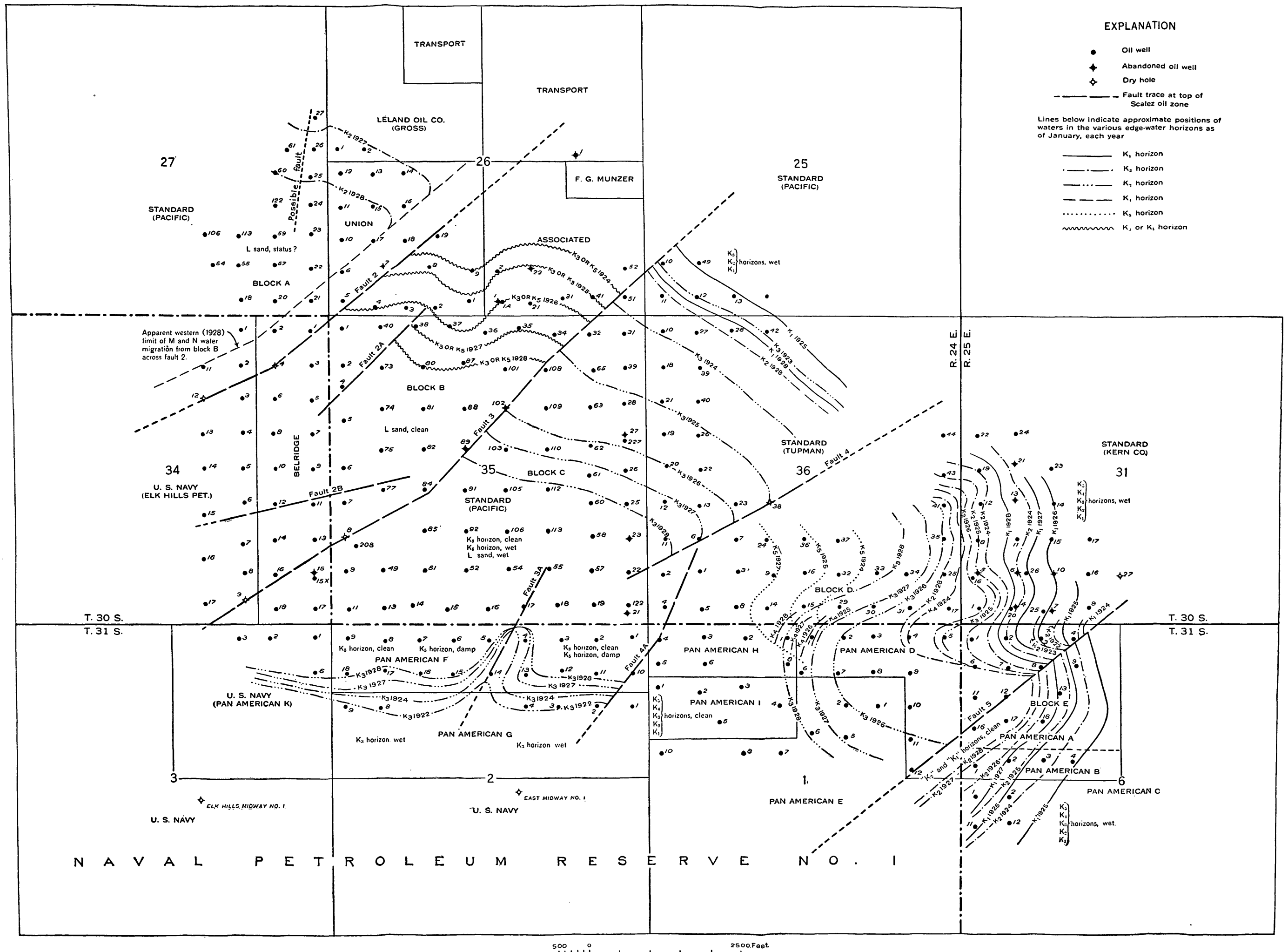


CURVES SHOWING PRODUCTION OF ELK HILLS





MAP SHOWING LOCATION OF WATERS LYING ABOVE SCALEZ OIL ZONE AND MIGRATION OF ALIEN WATERS ACROSS FAULTS IN EASTERN FIELD, ELK HILLS



MAP SHOWING LOCATION OF EDGE WATERS ENCROACHING WITHIN SCALEZ OIL ZONE AND OF WATERS LYING BELOW THIS ZONE IN EASTERN FIELD, ELK HILLS

field up to October, 1928, were examined, and from these records the sands open to production, character of production, and sources of water intrusion were determined. It soon became apparent that little progress in the identification and tracing of fluids could be made until the details of structure were known. It also became evident that in the determination of the structure, particularly with reference to slight displacements, the results revealed by the usual subsurface structure sections could not be considered conclusive without the supporting evidence of the movements of the fluids. The danger of falling into a vicious circle of reasoning was avoided so far as possible by checking against reliable evidence, such as the occurrence of the *Scales* bed or some other recognizable bed and the movements of the fluid contents of a readily recognizable sand. For example, on account of the relative thinness and stratigraphic isolation of the upper or K oil sand, any break in its continuity is generally revealed by the nature of the movements of fluids through it.

It might be objected that the evidence of subsurface faults can not be considered reliable in the light of what is known about the lateral drift of bore holes.<sup>71</sup> Though no survey has been made of the wells in the Elk Hills, it is apparent from the following considerations that there is no reason to believe that they have drifted so far from vertical that the subsurface records are seriously affected. The wells are relatively shallow; even surveyed holes that show a marked lateral drift are generally vertical to a depth of 2,500 or 3,000 feet. Almost all the wells were drilled by the operating companies and not under contract. They were drilled under normal conditions without the incentive to "make hole" rapidly that accompanies closely spaced locations and competitive line drilling. They were drilled before modern high-pressure equipment was available. The beds penetrated are uniformly uncemented and relatively soft, and no trouble was experienced with caving. It is the practice to use only one water string, which is generally landed in the lower part of the hole immediately above the lower or *Scales* oil zone; if another string has been used in order to test or produce the upper oil sand, its shoe is rarely located more than 65 feet above the top of the lower oil zone.<sup>72</sup>

Moreover, the position assigned to the faults is based on the movement of the fluids, as well as on stratigraphic evidence. Three of the faults, Nos. 2 to 4, can be observed at the surface. The others, whose existence is deduced primarily from the behavior of fluids, supported

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<sup>71</sup> See especially Anderson, Alexander, Underground surveys of oil wells, a paper read before the New York meeting of the petroleum division of the American Institute of Mining and Metallurgical Engineers, February, 1929.

<sup>72</sup> See Farnsworth, H. R., The relation of bore holes to the vertical and the effect on geological conclusions: Oil Bull., vol. 16, No. 4, p. 388, 1930.

by stratigraphic evidence indicating a rupture or a sharp flexure, have so slight a displacement (10 to 55 feet) that they may fail to reach the surface or may have been overlooked.

Faults 2 to 5 bound areas in which the movements of the fluids are largely independent. These areas are designated from west to east blocks A, B, C, D, and E. (See pl. 13.)

### OCCURRENCE

Fourteen water-bearing beds or zones have been recognized in the eastern field. The beds are designated by letters to conform to local usage. Their designation, position, thickness (when known from coring or otherwise identified as being limited at any particular well location to certain definite sands), and static fluid levels are as follows:

#### *Waters in eastern field, Elk Hills*

| Water-bearing bed or zone         | Approximate interval above or below top of Scaletz oil zone | Approximate thickness | Character of bed                | Approximate average depth of static fluid level                                            |                                                                                                                                                 |
|-----------------------------------|-------------------------------------------------------------|-----------------------|---------------------------------|--------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
|                                   |                                                             |                       |                                 | Surface as datum plane                                                                     | Sea level as datum plane                                                                                                                        |
| Upper waters:                     | <i>Feet</i>                                                 | <i>Feet</i>           |                                 | <i>Feet</i>                                                                                | <i>Feet</i>                                                                                                                                     |
| G.....                            | +1,200.....                                                 | 18                    | Sand.....                       | -----                                                                                      | -----                                                                                                                                           |
| H.....                            | +1,120.....                                                 | 10                    | do.....                         | -----                                                                                      | -----                                                                                                                                           |
| H <sub>1</sub> .....              | +335.....                                                   | 15                    | do.....                         | -----                                                                                      | -----                                                                                                                                           |
| I.....                            | +170 to +260..                                              | 10-20                 | do.....                         | -----                                                                                      | -----                                                                                                                                           |
| J.....                            | +55 to +150;<br>average<br>+110. <sup>c</sup>               | 4-14                  | do.....                         | -250 to -500; will not bail below -350.<br>-200 to -675; will not bail below -350 to -700. | +150 to +300 <sup>a</sup> ; will not bail below +210. <sup>b</sup><br>+135 to +385 <sup>d</sup> ; will not bail below +35 to +195. <sup>e</sup> |
| Edge waters:                      |                                                             |                       |                                 |                                                                                            |                                                                                                                                                 |
| K.....                            | +12 to +60;<br>average<br>+40. <sup>c</sup>                 | 1-25                  | do.....                         | -600 to -670; will not bail below -600 to -900.                                            | +95 to +175 <sup>a</sup> ; will not bail below +175 to -85. <sup>b</sup>                                                                        |
| K <sub>1</sub> .....              | 0.....                                                      | -----                 | -----                           | -2,800.....                                                                                | -2,130. <sup>f</sup>                                                                                                                            |
| K <sub>2</sub> .....              | -38 to -50.....                                             | -----                 | -----                           | -500..... -2,000,                                                                          | +98..... -1,329                                                                                                                                 |
| K <sub>3</sub> <sup>h</sup> ..... | -80 to -112.....                                            | -----                 | -----                           | -2,850. <sup>i</sup>                                                                       | -2,138.                                                                                                                                         |
| K <sub>4</sub> <sup>k</sup> ..... | -132 to -142.....                                           | 6                     | Sand.....                       | -1,975.....                                                                                | -1,265. <sup>m</sup>                                                                                                                            |
| L.....                            | -180 to -210.....                                           | 2-8-10                | do.....                         | -----                                                                                      | -----                                                                                                                                           |
| Lower waters:                     |                                                             |                       |                                 |                                                                                            |                                                                                                                                                 |
| M.....                            | -256 to -275.....                                           | 5-20                  | Sandy shale.....                | -1,100.....                                                                                | -125. <sup>n</sup>                                                                                                                              |
| N.....                            | -318 to -327.....                                           | 17                    | Fine sand with shale stringers. | -925.....                                                                                  | +55. <sup>n</sup>                                                                                                                               |
| O.....                            | -360.....                                                   | 16                    | Gray sand.....                  | -----                                                                                      | -----                                                                                                                                           |

<sup>a</sup> Data from Union wells 7, 18, Associated wells 1 and 52, sec. 26.

<sup>b</sup> Data from Union well 1, sec. 26.

<sup>c</sup> The minimum intervals shown for the J and K sands are found chiefly along the axial part of the anticline.

<sup>d</sup> Data from Associated wells 21, 41, 52, sec. 26; Pan American wells 2 A, sec. 6, 2 F, sec. 1, and 1 F, sec. 2.

<sup>e</sup> Data from Associated wells 1, 2, 52, sec. 26; Pan American wells 7 E, sec. 1, 1 F, sec. 2.

<sup>f</sup> Classed as upper water if sand is saturated with water throughout a block.

<sup>g</sup> Data from Pan American wells 3 D, sec. 1, and 3 F, sec. 2.

<sup>h</sup> Data from Pan American wells 3 A, sec. 6, 8 E, sec. 1, and 2 F, sec. 2.

<sup>i</sup> Data from Pan American well 2 A, sec. 6.

<sup>j</sup> These widely varying data are taken respectively from Pan American wells 4 A, 2 A, sec. 6, and 4 D, sec. 1.

<sup>k</sup> Classed as lower waters if sand is saturated with water throughout block.

<sup>l</sup> For discussion of the K<sub>4</sub> zone see p. 77.

<sup>m</sup> Data from Pan American well 4 D, sec. 1.

<sup>n</sup> Data from U. S. Navy well Elk Hills Petroleum No. 9, sec. 34.

The stratigraphic relations of the water-bearing beds are shown graphically in Figures 6 and 7.

The upper waters are in the beds that lie above the productive oil-bearing beds. The edge waters are those that have advanced up the slope through the productive sands embraced in the upper oil sand and the lower or *Scales* oil zones, which together represent the upper part of the B oil zone. Waters in the lower part of this group are classed as lower waters if the sand is saturated with water throughout a block. The lower waters are in the beds that lie below the productive beds of the *Scales* oil zone. The water-bearing beds of this group are embraced within an unproductive vertical interval of about 200 feet corresponding to the middle division of the Sunset-Midway field.<sup>73</sup>

### CHEMICAL CHARACTERISTICS

Through the kindness of the officials of the Associated Oil Co. the following analyses are reproduced from an unpublished report by L. A. Penn:

#### *Analyses of Elk Hills waters*

[L. A. Penn, analyst. Per cent except as otherwise designated]

| Class of water                                       | Total mineral content (parts per million) | Alkalies | Earths | Calcium | Magnesium | Sulphate | Chloride | Carbonate | Primary salinity | Primary alkalinity | Secondary salinity | Secondary alkalinity | Carbonate-chloride ratio | Calcium-magnesium ratio |
|------------------------------------------------------|-------------------------------------------|----------|--------|---------|-----------|----------|----------|-----------|------------------|--------------------|--------------------|----------------------|--------------------------|-------------------------|
| G.....                                               | 35,901.3                                  | 40.30    | 9.70   | 5.36    | 4.34      | 0.13     | 49.71    | 0.16      | 80.60            | .....              | 19.08              | 0.32                 | 0.003                    | 1.24                    |
| H.....                                               | 24,055.7                                  | 43.48    | 6.52   | 2.72    | 3.80      | .08      | 49.49    | .43       | 86.96            | .....              | 12.12              | .86                  | .009                     | .72                     |
| I.....                                               | 42,402.7                                  | 38.84    | 11.16  | 7.61    | 3.55      | .15      | 49.51    | .34       | 77.68            | .....              | 21.64              | .68                  | .007                     | 2.14                    |
| J.....                                               | 39,739.5                                  | 40.17    | 9.83   | 7.48    | 2.35      | .16      | 49.61    | .23       | 80.34            | .....              | 19.20              | .46                  | .005                     | 3.14                    |
| K <sub>1</sub> +K <sub>2</sub> +K <sub>3</sub> ..... | 31,610.8                                  | 43.23    | 6.77   | 6.55    | .22       | .31      | 49.33    | .36       | 86.46            | .....              | 12.83              | .71                  | .007                     | 29.77                   |
| L.....                                               | 36,124.5                                  | 40.42    | 9.58   | 5.11    | 4.47      | .12      | 49.47    | .41       | 80.84            | .....              | 18.35              | .81                  | .008                     | 1.14                    |

All these waters are brines varying in mineral content, in round numbers, from 24,000 to 42,000 parts per million. In general features they are similar, but they can usually be recognized by slight differences. The characteristic features are summarized by Mr. Penn as follows:

G, primary salinity 80 per cent, secondary salinity 19 per cent, calcium slightly higher than magnesium, and earths 9.7 per cent.

H, primary salinity 87 per cent, secondary salinity 12 per cent, calcium less than magnesium, and earths 6.5 per cent.

I, alkalies 38.8 per cent, calcium 7.6 per cent, magnesium 3.5 per cent, primary salinity 77.5 per cent, secondary salinity 21.6 per cent, calcium-magnesium ratio of 2.1, and earths 11 per cent.

J, alkalies 40 per cent, calcium 7.5 per cent, magnesium 2.3 per cent, primary salinity 80 per cent, secondary salinity 19 per cent, calcium-magnesium ratio of 3, and earths 9.8 per cent.

<sup>73</sup> Pack, R. W., U. S. Geol. Survey Prof. Paper 116, pp. 141-142, 1920.

$K_1 + K_2 + K_3$  (a mixture), alkalis 43 per cent, calcium 6.5 per cent, magnesium 0.2 per cent, primary salinity 86.5 per cent, secondary salinity 12.8 per cent, calcium-magnesium ratio above 25.0, and earths 6.8 per cent. This mixture is very similar in character to class H water but is distinguished from it by the high calcium-magnesium ratio.

L, calcium 5 per cent, magnesium 4.5 per cent, primary salinity 80.8 per cent, secondary salinity 18 per cent, calcium-magnesium ratio about 1.0. This water is very similar to class J water but is distinguished from it by the lower calcium-magnesium ratio.

## MOVEMENTS OF THE WATERS

### BLOCK A

*Structure.*—Block A (see pl. 13) is bounded on the southeast by fault 2 and presumably on the northwest by fault 1, which, however, has not yet been revealed by drilling. A generalized section showing the position of the oil and water sands along faults 2 and 3 is given in Figure 8. Fault 2 was recognized early in the history of the field. It is demonstrated both by the stratigraphic records of wells, illustrated in a striking manner by the difference in depth of the *Scaletz* bed in the adjoining wells 18 and 19 of the Union Oil Co., in section 26, and by the nature of the movement of the waters, which is entirely independent on the two sides of the fault. The J and K sands, which are normally water bearing or "wet" in block A, show an unusual impregnation of oil in this block in wells drilled close to the fault plane. This condition may be due either to migration of oil

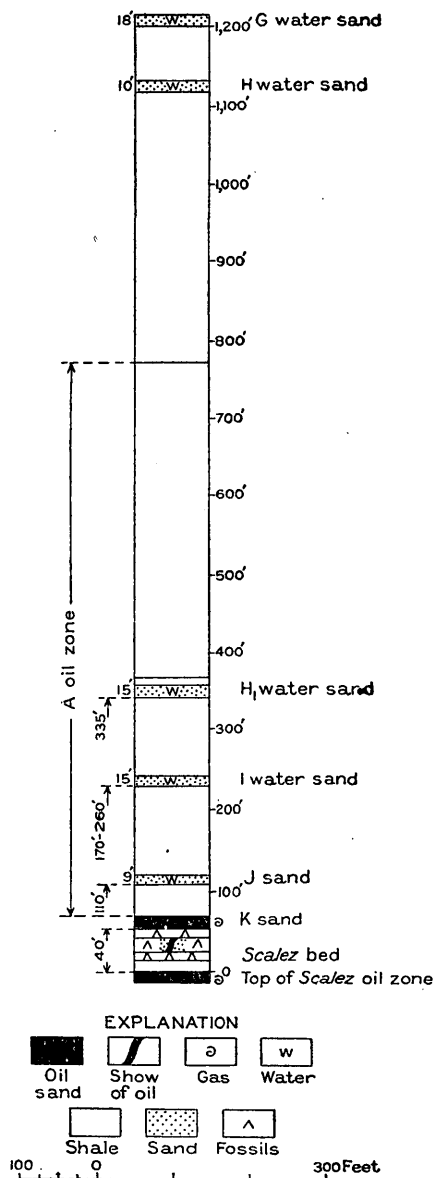


FIGURE 6.—Water-bearing beds lying above *Scaletz* oil zone of eastern field

native to the *Scaletz* oil zone on the footwall westward across the fault or to accumulation against the fault of oil and gas moving up the north flank of the anticline. U. S. Navy well Elk Hills Petro-

leum No. 12 and Belridge Oil Co. well No. 4, in section 34, which were started on the downthrown side of the fault and penetrated the fault plane at the horizon of the *Scaletz* oil zone, were found to be commercially unproductive, doubtless owing to the displacement of the oil and water sands and to movements of fluids across the fault.

*Migration of water westward across fault 2.*—The relative position of the oil and water sands along fault 2 is shown in the generalized section, Figure 8, and on Plates 18, 19, and 20. From these sections it is apparent that the high-head waters in the M and N sands of block B are in a position to migrate westward across the fault into the sands of the *Scaletz* oil zone in block A. After the dissipation of initial rock pressures these waters will appear in wells close to the fault in which these oil sands are open to production. The western limit of migration of this alien water in 1928 is shown on Plate 16. Some of the wells within the area shown on Plate 16 as affected by this migration are also open to the wet K oil sand or are within reach of advancing  $K_2$  edge water. (See pl. 17.)

*Upper waters.*—The I sand is definitely known to be water bearing in block A

and carries water under high head. Both the J sand and the K oil sand are also known to be wet throughout this block. The move-

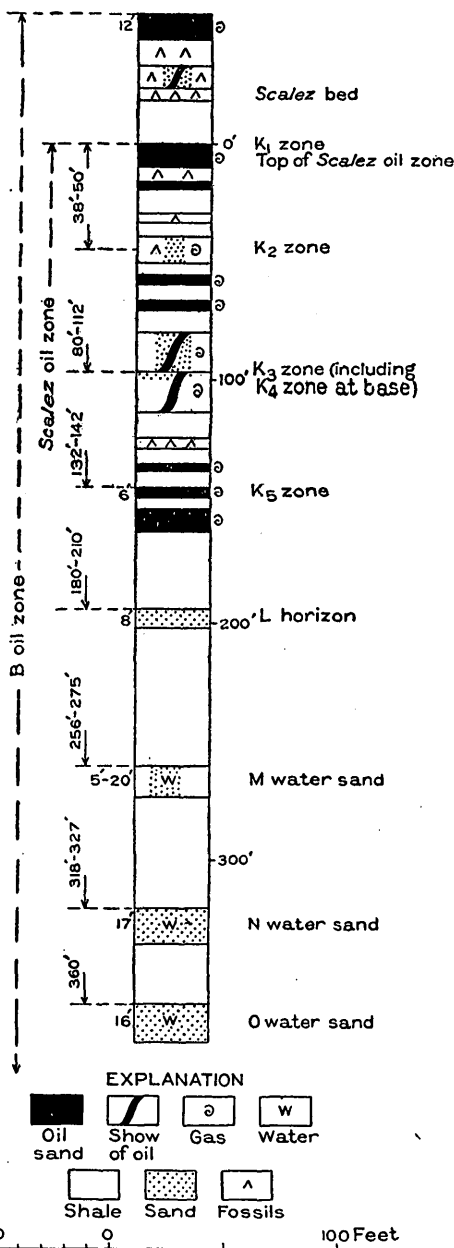


FIGURE 7.—Water-bearing beds lying within and below *Scaletz* oil zone of eastern field

ment of the water in these two sands is somewhat affected, close to the fault, however, by the back pressure of the oil and gas that have accumulated against it. In wells in which the K oil sand was left open to production water subsequently appeared, and this sand had

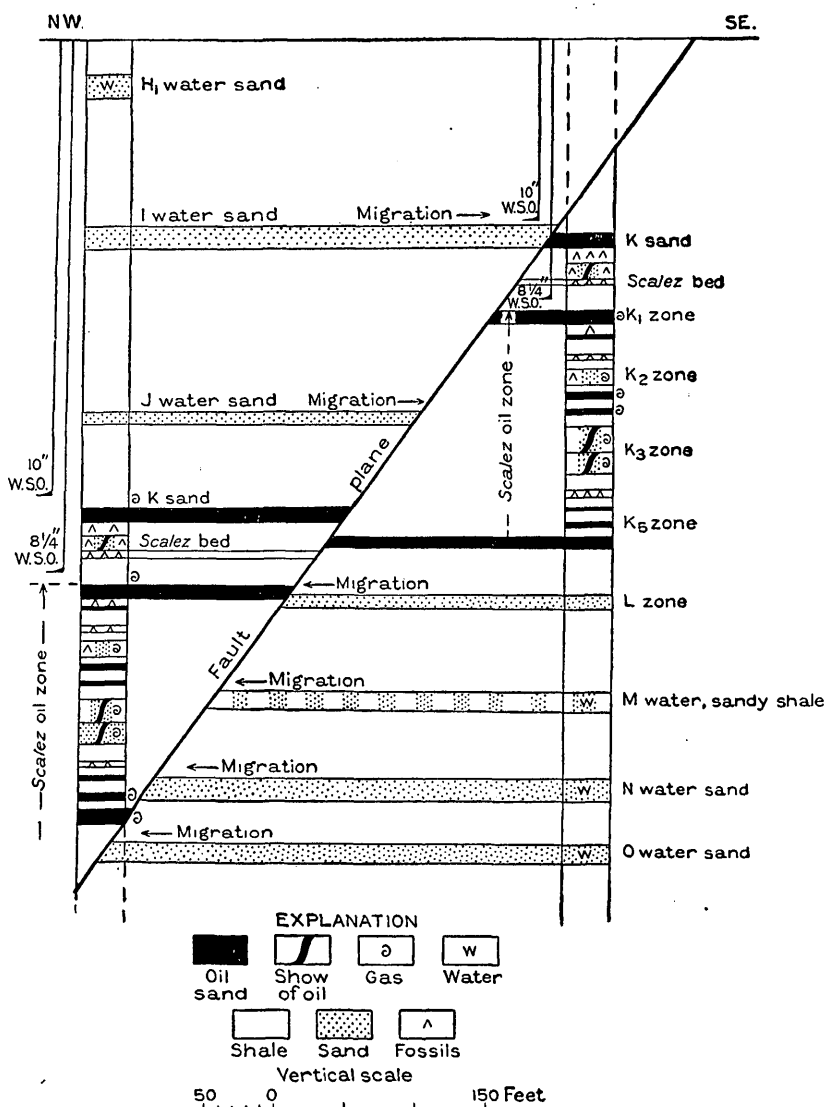


FIGURE 8.—Generalized section showing displacement along faults 2 and 3

to be cased off to get "clean production." (See graph of well Pacific No. 21, sec. 27, on pl. 19.)

*Lower waters.*—Apparently no well within block A has been drilled deep enough to penetrate the L sand. The deepest wells, which have an interval of 114 to 160 feet of beds below the top of



the *Scales* oil zone open to production, yielded clean oil during their early life, and the waters now appearing in some of them are edge waters.

*Intermediate waters.*—Only one zone within the productive beds in the developed part of block A seems to be now affected by native edge water. In view of the high fluid level of the water that broke into Union Oil Co. well No. 14, in section 26—a characteristic feature of  $K_2$  water under conditions of water saturation so far as intermediate and lower waters are concerned—and in view of the bridging of the hole with sand at a depth of about 60 feet below the top of the *Scales* oil zone when the water broke in, this intermediate water is considered  $K_2$  edge water, though the exact depth of intrusion has not yet been adequately determined. The progress of this water up the fold is shown on Plate 17.

The water appearing in the wells in the eastern part of section 27 is represented on Plate 17 as normally advancing  $K_2$  edge water. It may, however, be interpreted as coming from some other source on the assumption that the beds are broken along a fault with a displacement of about 40 feet along the dotted line shown on Plate 17, instead of being folded into a synclinal trough as shown on Plate 13. If the beds are faulted the wet K oil sand on the west would be dropped against the upper beds of the *Scales* oil zone on the east, and these beds would be open to migration of water eastward across the fault. Such migration may account for the water that appeared early in the life of well Pacific No. 27 and later in wells Nos. 26, 25, 24, and 23 at dates representing progressively greater intervals of time subsequent to the dates of completion. On the same assumption the water that appeared in wells Nos. 60 and 61 might be alien  $K_2$  water migrating westward across the fault. The uncertainty as to whether the water in wells Nos. 60 and 61 is due to lateral alien migration from the east or to normally advancing  $K_2$  edge water could perhaps be settled by determining whether the wet horizon is at the top of the *Scales* oil zone or approximately 50 feet lower. A high fluid level should be found if native  $K_2$  edge water is present in large quantities. Though the production of well No. 61 in 1928 was about 60 per cent water, the fluid level generally stands at 900 feet below the surface, which seems to be too low for native  $K_2$  edge water.

#### BLOCK B

*Structure.*—Block B lies between faults 2 and 3. The existence of fault 3, as well as fault 2, was suspected early in the development of this part of the field, on account of the unusual difficulties attending the exclusion of water and the production of clean oil in wells penetrating it or drilled close to it. The sharply defined break in the

*Scales* bed and other marker beds was not definitely established, however, until after the use of the core barrel became general. The stratigraphic record of U. S. Navy well Elk Hills Petroleum No. 9 is particularly instructive. After it had passed through the K (upper) oil sand, the first *Amnicola* bed, the sandy "shale" stringer carrying ostracodes and showing colors of oil, and the *Scales* bed were penetrated in normal succession. But at the depth where the top member of the *Scales* oil zone should have been encountered the bit plunged into "sticky blue shale" and passed through unproductive beds known to underlie the oil zone. The displacement is also clearly shown by the movement of the waters.

The recognition of minor faults 2 A and 2 B within block B is based on stratigraphic evidence supported by the fluid content of the K sand, as will be brought out in the discussion of the movement of water through it. Fault 2 A has a maximum displacement of about 55 feet, and 2 B about 35 feet. These faults are shown in the sections on Plates 18, 19, and 20.

*Migration of water southward across fault 2.*—As shown in Figure 8 and in Plates 18, 19, and 20, the I, J, and K sands of block A are dropped against the productive beds of block B along fault 2. The waters in the J and K sands of block A need not be considered, as no important infiltration of water from them into the lower part of the *Scales* oil zone of block B, against which they lie, has been found, probably because of the accumulation of oil and gas in these sands in block A along the fault. The I sand of block A carries water under high head, and this water has a pronounced effect on the casing program and on the production of wells within part of block B. As shown on the structure sections cited above, the I sand of block A is dropped down along the fault about to the level of the K oil sand of block B. This relation has resulted in a widespread flooding of the productive K sand in block B by the infiltration of alien I water. The probable eastern limit of this alien migration, of which faults 2 A and 2 B form a part, is shown on Plate 16. Between the two faults the limit of migration is determined by Standard Oil Co. wells Pacific Nos. 74 and 82, which are open to production from the K sand and are producing clean oil. In 1922 the K sand was found to be wet in the original drilling of wells Belridge No. 3 and Pacific Nos. 1 and 2; nevertheless six years later, in Pacific No. 73, but one location to the east, clean oil was produced. Likewise, although the K sand was found to be wet and was cased off in 1924-25 during the original drilling of Pacific Nos. 4, 5, and 6 and Belridge Nos. 5, 7, 9, and 12, it has during the four years 1925-1928 yielded clean oil in Belridge Nos. 11 and 13 and Pacific Nos. 7 and 77. These conditions are difficult to understand

without assuming the presence of faults 2 A and 2 B, which would act as barriers against the progress of the water migrating up the slope through the K sand, instead of possible sharp flexures along these trends.

*Migration of water westward across fault 3.*—Alien water migrates across fault 3 in much the same manner as across fault 2. (See fig. 8 and pls. 19 and 20.) There is one important difference, however. The L sand in block B is devoid of water, whereas in block C it is one of the chief lower-water sands. Consequently along fault 3 the *Scalez* oil zone of block B is subject to alien migration not only from the M and N sands of block C but also from the overlying L sand. This condition doubtless accounts for the failure of wells started in block B and completed in or close to the fault to obtain commercial production. U. S. Navy well, Elk Hills Petroleum No. 9, section 34, and Standard Oil Co. wells Pacific Nos. 8, 89, and 102 had to be abandoned. It is not possible to trace any gradual westward movement in this migration, presumably because the oil and gas of the *Scalez* oil zone in block B are under high pressure.

*Upper waters.*—Both the I and J sands of block B are known to be wet, the former carrying water under a particularly high head. Many of the wells in this block, especially those along the boundary between sections 26 and 35, have been open to production from these sands, and it has been necessary to cement additional strings of casing to shut them off.

The value of chemical analyses in identifying oil-field waters is illustrated by the history of Associated Oil Co. well No. 52 in section 26. When this well was drilled in 1924 the presence of fault 3, or at least its extension so far north, was not known. Consequently the estimated depth at which the top of the *Scalez* oil zone was to be encountered, in accordance with which the water string was landed, was about 230 feet too high. The estimate for the top of the *Scalez* oil zone though erroneous, appeared at that time to be verified by shows of oil that had migrated westward across the fault. After testing the water shut-off the hole was cleaned out and drilled ahead to a completion depth 109 feet below the shoe. When the well was bailed and swabbed to bring it in, water broke in and rose rapidly to a level about 250 feet below the surface. A sample of this water was sent to the company's laboratory, where it was analyzed by L. A. Penn and reported as J water. This identification by the chemist was considered at that time to be opposed to the stratigraphic and paleontologic evidence as it was then understood. Later the well was deepened, the top of the *Scalez* oil zone was located, and it was found that the water was coming in at a depth of about 130 feet above the top of this oil zone, the chemist's identification being

thus confirmed. The water was shut off by landing and cementing an additional string of casing.

The damage to the K oil sand by the infiltration of alien I water from block A has already been described. The K sand also apparently carries edge water advancing up the slope, the annual progress of which is shown on Plate 16. The fluid from the wells in section 26 and along the north line of section 35 that are open to production from the K sand but are not open to any other probable water-bearing beds rarely shows more than 6 to 8 per cent of water.

*Intermediate waters.*—In addition to those wells in which the source of water is believed to be edge water from the K sand, other wells in the area far down on the slope in block B that are subject to the same periods of edge-water encroachment show an initial cut of as much as 10 per cent water, which thereafter rapidly increases to as much as 50 per cent. Some of the well records indicate that this intrusion comes from the K<sub>5</sub> edge-water zone. An inconclusive test made by the Pacific Oil Co., in well No. 37, in section 35, indicates that the source of the water would fall within the K<sub>3</sub> edge-water zone. Until decisive tests are carried out this water is considered as either K<sub>3</sub> or K<sub>5</sub> edge water. Its annual progress is shown on Plate 17.

*Lower waters.*—The L sand is found to carry clean oil within block B. The M and N sands are not within the depth limit of the producing wells.

#### BLOCK C

*Structure.*—Block C is bounded on the northwest by fault 3 and on the southeast by faults 4 and 4 A. No definite *Scales* records are available for the wells along fault 4. The presence of this fault is deduced from stratigraphic evidence developed without these records, from the difference in horizon of encroaching edge water on the two sides, as described on following pages and as shown on Plate 17, and from the failure of well No. 38, in section 36, to yield oil in commercial amounts. This well, which was drilled during the early life of the field, had a normal prospect of successful completion. According to the view here taken, the first oil shows, encountered at a depth of 3,070 to 3,075 feet, represent the top of the *Scales* oil zone on the downthrown side of the fault. The hole then passed through the fault and was finished on the footwall at a horizon about 480 feet below the top of the *Scales* oil zone. Sands that appear to be the L and M water sands were logged at respective depths of 198 and 295 feet below the top of the *Scales* oil zone on the footwall. The failure of this well is similar to the failure of wells drilled through faults 2 and 3. Fault 4 is considered to have a maximum displace-

ment of about 65 feet, and, like the others so far discussed, is downthrown on the west side. Toward the southwest it passes into a shallow syncline. It was recognized at the surface at one locality.

Fault 4 A, unlike all the others recognized, has the downthrown side on the east. It has a maximum displacement of 45 feet. The recognition of this fault is based not only on the stratigraphic evidence but on the different content of the sands on the two sides. East of the fault the K sand and sands within the *Scales* oil zone carry gas under high pressure. When Pan American Petroleum Co. well No. 3 H, in section 1, came in it blew out from the K sand and produced uncontrolled for a period of five days, with an estimated daily flow of 75,000,000 cubic feet of gas under an estimated pressure of more than 1,000 pounds to the square inch. Likewise, during cleaning-out operations after a shut-in period of 56 days it blew out four times from a depth about 127 feet below the top of the *Scales* oil zone, or immediately below the K<sub>2</sub> horizon. Other Pan American and Standard wells in this region east of the fault yielded large quantities of gas under high pressure, and immediately after completion some of them produced only gas. The contrast between the initial production of wells on the two sides of the fault is shown in the following table.

*Initial production of wells on each side of fault 4 A*

| West of fault                  |                    |                                            |                     | East of fault                 |                    |                                                              |                                                          |
|--------------------------------|--------------------|--------------------------------------------|---------------------|-------------------------------|--------------------|--------------------------------------------------------------|----------------------------------------------------------|
| Well                           | Pumping or flowing | Initial daily production                   |                     | Well                          | Pumping or flowing | Initial daily production                                     |                                                          |
|                                |                    | Quantity                                   | Date                |                               |                    | Quantity                                                     | Date                                                     |
| Tupman No. 2, sec. 36.--       | F                  | 1,916 barrels oil (average first 18 days). | Sept. 13, 1920----- | Tupman No. 1, sec. 36.--      | F                  | 5,220 barrels oil (average of first 18 days).                | Feb. 10, 1920.                                           |
| Tupman No. 4, sec. 36.--       | F                  | 5,403 barrels oil-----                     | Sept. 6, 1920-----  | Tupman No. 5, sec. 36.--      | F                  | 8,705 barrels (average first 4 days).                        | Aug. 28, 1920.                                           |
| Pan American No. 1 F, sec. 2.  | P                  | 36 barrels oil-----                        | July 4, 1922-----   | Pan American No. 3 H, sec. 1. | F                  | 75,000,000 cubic feet gas (est.).                            | Dec. 15-19, 1921.                                        |
| Pan American No. 11-F, sec. 2. | P                  | 243 barrels oil (average first 30 days).   | Sept. 8, 1924-----  | Pan American No. 1-I, sec. 1. | F                  | 3,328,000 cubic feet gas-----                                | Dec. 30, 1921.                                           |
| Pan American No. 2 G, sec. 2.  | P                  | 156 barrels oil (average first 30 days).   | Nov. 21, 1922-----  | Pan American No. 1 G, sec. 2. | F                  | Started oil-----<br>196 barrels oil (average first 30 days). | May 1922<br>Jan. 22, 1926 (after redrilling oil string). |
|                                |                    |                                            |                     |                               | F                  | 1,445 barrels oil (average first 30 days).                   | May 22, 1922.                                            |

Pan American No. 1 F, in section 2, affords a further contrast. The upper 140 feet of the *Scales* oil zone in this well apparently became exhausted in October, 1925, and operations have practically been suspended since then. In No. 2 G, in section 2, the upper 86 feet of the *Scales* oil zone was found to be unproductive, and it was necessary to deepen the hole to a depth of 105 feet below the top of this zone before commercial production was obtained. The K oil sand showed no impregnation of oil or gas in wells Nos. 4 H and 1 F, a slight showing of gas in No. 2 F, oil and gas in No. 3 F, and oil saturation in No. 4 F. The lack of adequate drainage area available to the wells located immediately west of the fault seems to have a vital effect on their productivity. In contrast to the situation west of the fault, the Pan American wells immediately east of the fault not only had a high initial yield, but they were still continuing, in 1928, to produce large quantities of clean oil and gas from these same sands. The gas pressure in these wells, especially that contributed by the K sand, is still great enough to hold back the encroaching edge waters to positions relatively far down the dip. On the west side of the fault, however, the K sand is now occupied by edge water and the K beds in and underlying the K<sub>3</sub> zone in the underlying *Scales* oil zone are approaching the same condition.

In addition to the bounding faults, minor fault 3 A is postulated within block C. It has the downthrown side on the west and has an average displacement of about 10 feet. The content of the K sand on each side constitutes the evidence for its presence; west of the fault the K sand continues to produce clean oil, whereas east of it after a brief period of production in 1922 it was found to be wet.

*Migration of water southward across fault 3.*—Figure 8 and Plates 19 and 20 show the relations of the oil and water sands along fault 3. The beds of block C at and near the horizon of the K sand are raised against the I sand of block B, which carries water under high head. In a similar manner the middle part of the *Scales* oil zone of block C lies against the J water sand of block B. On the release of gas pressure the water from the I sand of block B migrates into the K sand and any other porous beds lying between the shoe of the water string and the top of the *Scales* oil zone, and the water from the J sand of block B finds its way into the *Scales* oil zone of block C. This alien I water has been identified in the Belridge Oil Co. well No. 18, section 34; the Standard Oil Co. wells Pacific Nos. 9, 11, and 208, section 35, and No. 10, section 25; and possibly also in Associated Oil Co. well No. 51, section 26. Alien J water has been identified in Belridge Oil Co. well No. 18, section 34, and in Standard Oil Co. wells Pacific Nos. 9, 11, and 208. Belridge Oil Co. well No. 15, in which part of the K sand and the beds immediately underlying it,

including 50 feet of the *Scalez* oil zone, were open to production (see pl. 19), showed alien I water migrating into the hole through beds lying immediately below the shoe of the water string, but it did not appear until after nine months of clean production, or until after the initial gas pressure had been dissipated. On the other hand, Belridge well No. 15 X, with the K oil sand and immediately underlying beds cased off, has not been affected by this alien water. The effect of structure on the limits of the area affected by the migration of the alien I and J waters is illustrated by Belridge well No. 17. In this well the K sand is open to production and the results of I water migration through or immediately below the K sand would ordinarily be expected. Gas pressures at the main anticlinal crest seem to be so high that further southward migration of the water is prevented for the time being. The probable eastern limit of migration of I and J water across the fault is shown on Plate 16.

*Migration of water westward across fault 3 A.*—The northward advance of edge water through the K sand in the area between faults 3 A and 4 A is described on page 73, in connection with the upper waters. This edge water migrates westward across fault 3 A and appears on its west side, as shown on Plate 16. The alien water can not move westward until after the high initial gas pressure in the productive beds west of the fault is released. The small water cut that made its appearance in Pan American Petroleum Co. well No. 5 F, in section 2, as late as 1925 is attributed to alien K water. Though well No. 17 of the Standard Oil Co., in section 35, lies close to the fault, the alien K water did not appear in this hole until November and December, 1925, after its normal appearance as native edge water east of the fault.

*Migration of water westward across faults 4 and 4 A.*—No migration of water westward across faults 4 and 4 A that affects the productivity of the *Scalez* oil zone was apparent in the fluid of any of the producing wells in 1928.

*Upper waters.*—In block C the I sand is definitely known to be water-bearing on both flanks of the anticline and carries water under a high head.

The J sand is predominantly a water sand on the flanks of the anticline. Along the crest in block C it has been found to contain sufficient quantities of oil and gas to yield practically clean production for variable periods of time. It is the only place in the eastern field where any bed lying above the B oil zone has yielded oil in commercial quantity. The accumulation of oil in this sand is particularly striking along the crest between faults 3 A and 4 A. In some of the wells near fault 3 A the J sand was logged in the original drilling as oil sand, and in two of them it has produced after casing



had been properly landed and cemented so as to exclude overlying waters. Soon, however, water appeared in this sand, and it had to be cased off. (See graphs of Pan American Petroleum Co. wells Nos. 3 F and 4 F, sec. 2, on pl. 21.) The unusual oil saturation of the J sand in the area between these two faults is probably due to the westward migration of oil from the *Scalez* oil zone of block D across fault 4 and to its subsequent movement southwestward up the slope to the barrier at the plane of fault 3 A. The water appearing in Standard Oil Co. well Pacific No. 13, in section 35, in 1924, and in Nos. 15 and 16, in the same section, in 1926, which has now been effectively excluded, is attributed to infiltration through the J sand.

The progress of edge water up the south slope of the anticline between faults 3 A and 4 A through the K oil sand is shown on Plate 16. Along the anticlinal crest the advance of this edge water has been retarded and temporarily stopped. The position of K edge water down the north flank in block C in 1928 is also shown on Plate 16. With the exception of the areas of wet K sand already described, most of the wells in Block C located up the slope from well Pacific No. 31, in section 35, are still open to production from the K sand and are now producing clean oil from it.

The different content of the K sand on the two sides of fault 3 A is described on page 71 in connection with the structure.

*Lower waters.*—Block C embraces the only area within the eastern field in which the presence of L water as a lower water has been definitely established. The L sand, which lies 180 to 210 feet below the top of the *Scalez* oil zone, has been penetrated by the relatively deep wells in this area. U. S. Navy well Elk Hills Petroleum Co. No. 9, in section 34, penetrated the L sand in the footwall of fault 3 just below the *Scalez* bed in the hanging wall and went down into the M and N sands. Later the M and N sands were properly plugged, but the L sand was left open and was found to be dry. The reason why it was dry at this location and wet elsewhere in block C where it was penetrated is not apparent.

Most of the deeper wells in block C were not cored continuously throughout the oil zone, and consequently the K<sub>s</sub> sand was not logged as water-bearing. In wells on the north slope that had the K<sub>s</sub> horizon open to production it immediately became necessary to plug the sand off in order to exclude the water. Therefore, the K<sub>s</sub> sand, the top of which generally lies 132 to 142 feet below the top of the *Scalez* oil zone, is considered one of the two known lower water-bearing beds in this block.

*Intermediate waters.*—The productive beds within the *Scalez* oil zone in block C that are affected by encroaching edge water are those

designated  $K_3$ ,  $K_2$ , and  $K_1$ . (See fig. 7.) The annual progress and position of these waters in 1928 are shown on Plate 17.

Edge water is present in the  $K_3$  zone, the top of which is 80 to 112 feet below the top of the *Scaletz* oil zone, on both the north and south flanks. The determination of the depth of intrusion on the south flank is based on positive mud tests and on the results of subsequent plugging. For the north flank the results of final plugging operations were used. The progress of  $K_3$  edge water up the north slope from 1923 to 1926 was much more rapid than from 1926 to 1928, when the annual rate was only about 450 feet.

The top of the  $K_2$  zone lies 38 to 50 feet below the top of the *Scaletz* oil zone, and the  $K_1$  zone embraces the uppermost beds of the *Scaletz* oil zone, including the "*Scaletz* finger," which lies at the top. The 1928 position of  $K_2$  edge water and the 1925 and 1928 positions of  $K_1$  water on the north slope are shown on Plate 17. It is impossible to determine the annual limits of encroachment of these waters, for most of the wells affected by them have been shut in for the last few years.

#### BLOCK D

*Structure.*—Block D lies between faults 4 and 4 A on the northwest and fault 5 on the southeast. A large amount of information on water encroachment is available for this area. Fault 5, which has an average displacement of about 35 feet with downthrow on the west side, is recognized by the marked difference in the movement of intermediate waters on the two sides, by the interference in the normal movement of gas and oil up the slope from block E, and by the following additional evidence of displacement. In Pan American well No. 16 A, section 6, the wet K sand was cased off back of the 10-inch water string. In wells Nos. 11 A and 6 A the 10-inch string was cemented at depths based on an assumption of uniform structure between these wells and No. 16 A, but this procedure failed to exclude the K water, and it was necessary to cement another string of casing at a depth approximately 50 feet lower, or at the top of the *Scaletz* oil zone, in order to shut off the water. The wells then produced clean oil. (See pl. 22, B.) Similar conditions are found elsewhere along the postulated fault. They doubtless were the cause for the using of two water strings in the original drilling of wells Nos. 11 D, 10 D, and 9 D, in section 1. (See pl. 22, A.) Well No. 12 A, in section 6, according to the view here taken, started on the north side of the fault, passed through the K (upper) oil sand, penetrated the top of the *Scaletz* oil zone at a depth of 3,347 feet, and then reached the fault plane about 50 feet lower. The performance

of this well as a producer has always been unlike the performance of the surrounding wells.

*Migration of water eastward across faults 4 and 4 A.*—The K oil sand of block C is dropped along fault 4 against beds ordinarily left open below water strings in wells completed in block D. Wells in block D along this fault are in no danger of alien water from this source until K water advances far up the north slope from its 1928 position. On the south slope west of fault 4 A the K sand is wet, but migration across the fault has not been detected, presumably because the K sand of block C lies against beds that are ordinarily placed behind the water strings of wells in block D. (See pls. 20, B, and 21.)

The wet J sand of block C apparently is not displaced enough along fault 4 to affect by alien migration wells completed in block D with the usual casing program.

*Migration of water westward across fault 5.*—Along fault 5 the wet K oil sand of block E is raised against sandy beds lying immediately above the K sand in block D. Apparently K water has migrated across the fault into block D. The approximate western limit of this migration is shown on Plate 16. (See also pls. 21 and 22.)

The water that appeared in well No. 4 A in May, 1924, and that rapidly increased the percentage of water in the fluid from well No. 8 A in August, 1926, is for the most part attributed to alien  $K_2$  edge water of block E migrating across the fault into the  $K_1$  zone, as a 35-foot displacement brings the top of the *Scalez* oil zone of these wells about opposite the wet  $K_2$  zone on the footwall in block E.

*Upper waters.*—The I and J sands are the only water-bearing beds above the upper (K) oil sand in block D with which the operator is primarily concerned. They are found at more or less uniform vertical intervals above the top of the *Scalez* oil sand but probably consist of a series of connected lenses rather than beds of uniform thickness. The water strings are cemented at levels below the J sand.

In the original drilling of many wells located below the 2,450-foot contour of the top of the *Scalez* oil zone the K oil sand was cored and found to be completely saturated with edge water. Up the slope from about this contour level the K oil sand has generally been left open to production for periods that varied in length according to the rapidity of the advance of K edge water up the slope and the quantity of local infiltration. The annual progress of the K edge water is represented on Plate 16. The pronounced effect on the pro-

ductivity of the K oil sand caused by an apparently impervious barrier along fault 4 A has already been described. The accumulation of gas in the sand east of the fault has had a marked effect in retarding the progress of edge water up the slope through it, an effect that is most apparent in the areas of more recent development, as in section 1. In the southern part of the Tupman lease and along the north line of section 1 the productive beds were subjected to an earlier and more intensive development, and in this area the progress of edge water has been relatively rapid, as shown in the following table:

*Rate of K edge water encroachment in block D along north line of sec. 1,  
T. 31 S., R. 24 E.*

| Wells                             | Period                             | Approximate annual progress |
|-----------------------------------|------------------------------------|-----------------------------|
|                                   |                                    | <i>Feet</i>                 |
| Pan American Nos. 3 D to 1 D..... | August, 1920, to August, 1922..... | 600                         |
| Pan American Nos. 1 D to 1 H..... | August, 1922, to March, 1924.....  | 175                         |
| Pan American Nos. 1 H to 3 H..... | March, 1924, to October, 1926..... | 550                         |

During the period from August, 1922, to March, 1924, when the rate of encroachment was unusually slow, most of the wells in this region were shut in.

Pan American wells Nos. 6 D and 6 E, in section 1, show unusual features with reference to the movement of K edge water. Well No. 6 D is still open to production from the K sand. According to the general movement, infiltration from this horizon should have affected the fluid in this hole in December, 1922, during the period of general shutdown, but for some unknown reason the water did not enter until March, 1927, when water was present also in the K<sub>2</sub> zone. No. 6 E, which likewise is open to the K sand, should also be within the influence of K edge water, but the fluid has remained virtually clean to date. The production of gas from this well has always been notably large, both in volume and in pressure, and available data point to the K sand as the chief source. The behavior of this well is apparently determined by an isolated gas reservoir or pocket in the K sand, in which the gas is under such high pressure that the edge water surrounding it has been excluded.

The unusual conditions illustrated by these two wells, apparently due to unusual changes in the porosity of the sand, naturally raise the question whether the evidence on which the presence of the minor faults is based can not be interpreted in the same manner. Perhaps it can, but the changes along the postulated faults are linear in extent, and for most of them more than one line of supporting evidence can be seen.

*Lower waters.*—The only available information as to the presence of L water as a lower water in block D is afforded by Standard Oil Co. well Tupman No. 38, in section 36. This well was drilled through fault 4 and finished at a depth of about 480 feet below the top of the *Scaletz* oil zone. Beds that appear to be the L and M sands were logged at depths of 198 and 295 feet, respectively, below the top of the *Scaletz* oil zone. As no oil or gas shows were logged at either horizon, it is probable that these sands carry water.

Standard Oil Co. well Kern County No. 10, in section 31, was deepened to a total depth of 4,605 feet, or about 1,300 feet below the top of the *Scaletz* oil zone. It was abandoned in 1926 after having blown out during the deepening operations with an estimated daily flow of fifty to seventy-five million cubic feet of dry gas that demolished the derrick and equipment. At that time the hole was open between depths of 3,300 and 4,580 feet, and the horizon of the gas reservoir is not known, nor is any precise information available as to the fluid contents of the individual beds within this interval.

A deep test well in this area, No. 27, in section 31, was drilled in 1928–29.

*Intermediate waters.*—In tracing the progress of edge water through the lower productive beds of the *Scaletz* oil zone within block D it was found convenient to recognize a  $K_4$  zone, the top of which lies from 115 to 130 feet below the top of the *Scaletz* oil zone and which may actually represent the lower part of the  $K_3$  zone. The annual progress of the intermediate edge waters through the  $K_5$ ,  $K_4$ ,  $K_3$ ,  $K_2$ ,  $K_1$  zones in block D is shown on Plate 17. The  $K_5$  zone was still clean within most of the W.  $\frac{1}{2}$  sec. 1 in 1927. The progress of edge water through the  $K_4$  zone is slower than that through the  $K_3$  zone.  $K_4$  water generally makes its appearance about two years before  $K_3$  water. (See the approach to Pan American well No. 1 D, sec. 1, pl. 17.) The relatively rapid rate of progress of  $K_3$  water in following up the advance of  $K_4$  water points to the conclusion that both zones are in the same sands and that there is no continuous shale break between them. The approximate rate of encroachment of edge water through these two zones during recent years is as follows:

*Rate of encroachment of  $K_4$  and  $K_3$  edge waters in block D*

| Zone        | Period    | Approximate annual progress |
|-------------|-----------|-----------------------------|
| $K_4$ ..... | 1925–1928 | <i>Feet</i><br>250          |
| $K_3$ ..... | 1926–1928 | 420                         |

A highly productive gas and oil sand was found at a depth of 126 to 138 feet below the top of the *Scalez* oil zone, corresponding to the  $K_4$  zone, in a number of wells in section 1, notably Nos. 1 I, 2 H, and 3 H. Well No. 3 H blew out four times from this sand. The relatively slow progress of  $K_4$  edge water is attributed to this high gas pressure. It should be noted that the main "kick" in the *Scalez* oil zone along the north line of the Union Oil Co. lease in section 26, far down the north flank in block A, is at the same stratigraphic level.

The entrance of  $K_2$  edge water into any producing well is generally accompanied by an immediate and serious loss of oil production. Under conditions approaching water saturation, as in Pan American Petroleum Co. well No. 4 A, in section 6, the static fluid level of this edge water is about 500 feet below the surface, the highest level of all known edge water in the *Scalez* oil zone and more nearly corresponding to the levels that characterize the upper waters. Plate 17 clearly shows that the progress of  $K_2$  water across block D is quite distinct from that across block E. The greatest "pull" at this horizon has been from the Tupman lease of the Standard Oil Co., in section 36, and from the Pan American D and H wells, in section 1, especially from the older line wells along the boundary between the two sections. The greatest advance of edge water has been up the slope toward this region of older and more complete development. Along fault 5 can be seen a pronounced lag in the movement of  $K_2$  water, due apparently to incomplete development toward the southwest in section 1. The approximate maximum rates of encroachment of  $K_2$  edge water are as follows:

*Maximum rate of encroachment of  $K_2$  edge water in block D*

[See also pl. 21]

| Wells                             | Period                               | Maximum annual progress |
|-----------------------------------|--------------------------------------|-------------------------|
|                                   |                                      | Feet                    |
| Pan American Nos. 4 A to 1 A..... | January, 1921, to January, 1926..... | 410                     |
| Pan American Nos. 1 A to 4 D..... | January, 1926, to January, 1928..... | 580                     |

Inasmuch as  $K_1$  water—edge water in the uppermost members of the *Scalez* oil zone—has been identified in blocks C and E, it should also be found down the slope in block D, which was developed as early and as completely as the other two blocks. The recognition of native  $K_1$  edge water in block D is complicated by the probable migration of  $K_2$  water westward across fault 5 into the  $K_1$  zone of block D, as already described. From tests in progress in June, 1928, at Pan American well No. 2 A, in section 6, the  $K_1$  zone seems to be

water bearing. This conclusion is supported by the condition of Standard Oil Co. well Kern County No. 26, in section 31, in which the  $K_1$  zone is the only one open to production and the fluid is wet. The percentage of water in Pan American well No. 3 A, in section 6, was 8 to 12 per cent during the period from April to August, 1925, increased rapidly to 40 per cent in the following month, and was 61 per cent in 1928. Though the lack of plugging and testing operations and the presence of native  $K_2$  water make definite recognition impossible, this rapid increase is probably due to the appearance of native  $K_1$  water. The well is rather too far from fault 5 to attribute much of the increase to alien  $K_2$  water migrating across the fault, and well No. 8 A, which lies close to the fault and is on about the same subsurface contour as well No. 3 A, did not receive its alien  $K_2$  water until August, 1926, or nearly one year after the major water intrusion into well No. 3 A. Likewise  $K_1$  water is probably the source of the intrusion of water found in well No. 4 A during May, 1924, in addition to alien  $K_2$  water that is doubtless coming into this hole. Plate 18 shows the progress of  $K_1$  water, in so far as it can be traced.

#### BLOCK E

*Structure.*—Block E lies on the eastward plunge of the anticline east of fault 5. Its structure is simple.

*Migration of water eastward across fault 5.*—The 35-foot displacement along fault 5 drops the wet K (upper) oil sand of block D against beds at and immediately overlying the top of the *Scaletz* oil zone in block E. (See pl. 22, B.) These beds in block E are probably affected to some extent along the fault plane by alien K water moving across it. Pan American well No. 16 A is the only one lying close enough to the fault to show this water. The small amount of water appearing in this well—2 to 5 per cent—is attributed to alien K water coming in beneath the shoe of the 10-inch water string. (See pl. 22, B.)

*Upper waters.*—The K oil sand is saturated with water in block E. Throughout section 6, and, in fact, at all locations drilled east of well No. 3 D, in section 1, the K sand was found to be wet at the time of original drilling and the water string was set below it.

*Lower waters.*—Both the  $K_3$  and  $K_5$  edge-water zones are wet throughout block E, where their waters are classed as lower waters. No well in this area has so far been drilled to a depth more than 148 feet below the top of the *Scaletz* oil zone. Therefore the status of the L sand is not known, but it is doubtless water bearing.

*Intermediate waters.*—Edge water is advancing westward through the  $K_2$  zone at an annual rate decreasing from about 300 feet in

1924-1927 to about 100 feet in 1927-28, as shown on Plate 17. Up the slope against fault 5, where the accumulation of oil and gas is greatest and where the most productive wells are located, the advance of  $K_2$  edge water has been successfully retarded, so that wells Nos. 16 A and 17 A, in which the upper 63 feet and 81 feet, respectively, of the *Scalez* oil zone are open, are still yielding virtually clean oil.

The progress of  $K_1$  edge water in block E is shown on Plate 17. On the lower slopes of the anticline  $K_1$  water appears from one to two years after  $K_2$  water at any given location. The sinuosities of the lines marking the limits of the advance of these two edge waters are about the same, except that the  $K_1$  lines follow more closely the subsurface contours of the slight depression between wells Nos. 1 B and 4 B.



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