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GEOLOGY AND PETROLEUM RESOURCES OF NORTHWESTERN KERN COUNTY CALIFORNIA

BY

WALTER A. ENGLISH

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GEOLOGY AND PETROLEUM RESOURCES OF NORTHWESTERN KERN COUNTY, CALIFORNIA.

By Walter A. English.

INTRODUCTION.

SCOPE OF REPORT.

The area treated in this report comprises about 200 square miles of hilly and mountainous country and about 350 square miles of the alluvium-covered San Joaquin Valley, in which the Lost Hills, North Belridge or Manel Minor, and Belridge oil fields are situated and in which there appear to be possibilities that other fields may be developed (see fig. 1). The discussion is practically confined to the areal geology and to the possibilities of finding oil in untested areas. Conditions in the developed fields are considered solely as a problem in structural geology, and no attempt is made to present a study of the details of underground conditions. This lack of treatment of the developed fields in detail is due both to the circumstances connected with the preparation of the report and to the writer's belief that the United States Geological Survey's field of greatest usefulness lies rather in the type of work here set forth than in the study of underground conditions of interest to engineers engaged in the work of development and production. The California State Mining Bureau is now making such studies in much more detail and keeping data obtained more nearly up to date than the Geological Survey, under existing conditions, would find possible. The reader is therefore referred for such data to the bureau mentioned.

FIELD WORK.

The field work on which this report is based was done by the writer, assisted by W. S. W. Kew, in the fall of 1916. Approximately two months was spent in the field. The writer originally planned to make this a joint report by himself and R. W. Pack, who was to contribute the discussion of the developed fields. However, owing to the pressure of other work, Mr. Pack's part will probably be much delayed, and it seems best to publish the results available at the present time.

The same field methods were followed as in previous work in California. Copies of the Geological Survey's topographic maps enlarged to a scale of 1½ inches to the mile were used as a base for recording field observations, and locations for plotting geologic

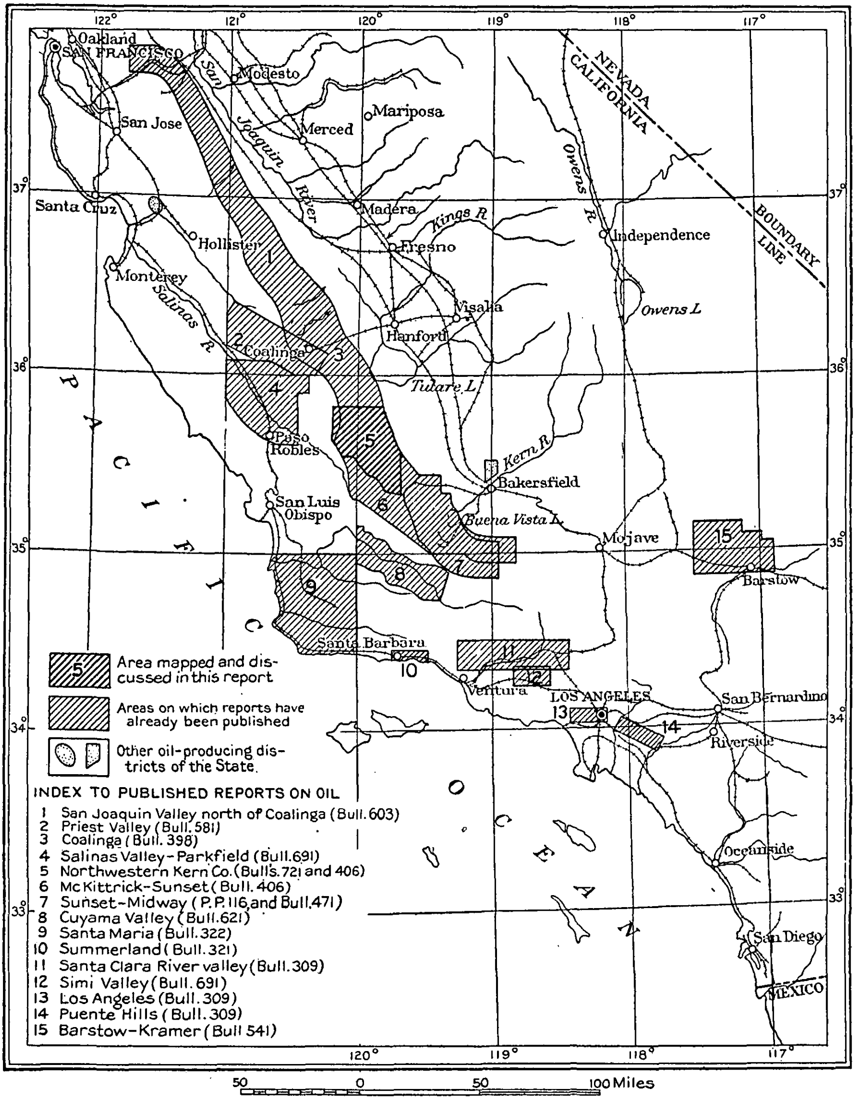


FIGURE 1.—Index map of southwestern California showing area considered in this report.

data were determined by the intersection of compass sights to prominent peaks or other features which it seemed probable had been accurately located by the topographers. Where details of topography seemed to be inaccurately shown, the areal geology as mapped (Pl. I) was adjusted to fit the topographic details only if no very material change was required. The geologic lines are therefore not in all places shown in their proper relation to the details of topography. No attempt was made to locate any section corners. The accuracy of the geologic lines with respect to section corners therefore depends on the accuracy with which these corners were located by the topographic engineers. Though the land net as shown is in all probability substantially correct, where an accurate tie between the geology and the land lines is desired the relations of the two should be checked.

PREVIOUS PUBLICATIONS.

The following list includes the papers dealing with the geology and petroleum resources of the general region considered in this bulletin that have appeared in recent years:

1894. Watts, W. L., The gas and petroleum yielding formations of the central valley of California: California State Min. Bur. Bull. 3, 100 pp., maps, plates, and figures. Sacramento.

Notes on the topography, geology, and oil resources of the Sunset district are given on pp. 22–37, and on the McKittrick district (called the Buena Vista district in Watts's report) on pp. 41–53; some analyses of water from the region are given on pp. 90 and 91.

1900. Watts, W. L., Oil and gas yielding formations of California: California State Min. Bur. Bull. 19, 236 pp., maps, plates, and figures. Sacramento.

Additional notes to those contained in his former report are given as follows: Geologic sketch of San Joaquin Valley, pp. 106–109; Sunset district, pp. 117–125; McKittrick district, pp. 125–131; Devils Den district, pp. 131 and 132.

1904. Prutzman, P. W., Production and uses of petroleum in California: California State Min. Bur. Bull. 32, 230 pp., maps, plates, figures, and tables. Sacramento.

Maps of the districts and analyses and notes concerning the physical and chemical properties of the oils, their uses, methods of refining, and other useful data are given in this bulletin.

1905. Anderson, F. M., A stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 3d ser., vol. 2, pp. 156–248, pls. 13 to 35, 1 map. San Francisco.

This paper includes a brief discussion of the geology and paleontology of the region along the southwestern side of San Joaquin Valley, including the region from Devils Den to Sunset, together with descriptions and illustrations of many of the fossils found in the Tertiary formations.

1908. Anderson, F. M., A further stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 4th ser., vol. 3, pp. 1–40, San Francisco.

In this paper Mr. Anderson gives a summary of his earlier paper and makes some corrections regarding the age of certain of the formations necessitated by a further study of the region.

1910. Arnold, Ralph, and Anderson, Robert, Geology and oil resources of the Coalinga district, Fresno and Kings counties, Calif.: U. S. Geol. Survey Bull. 398, 354 pp., maps, plates, figures, and tables.

This report includes a discussion of the geology and oil resources of the region immediately adjacent on the north to that covered by the present report. Many of the discussions apply to the McKittrick-Sunset region.

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.

Describes the geology of northwestern Kern County and gives results of drilling up to date of publication.

1914. McLaughlin, R. P., and Waring, C. A., Petroleum industry of California: California Min. Bur. Bull. 69.

Gives good description of Lost Hills and Belridge fields and map showing location of wells.

1917. Gester, G. C., Geology of a portion of the McKittrick district: California Acad. Sci. Proc., 4th ser., vol. 7, No. 9, pp. 207–227, pls. 33–34.

Points out the unconformable relations of the Maricopa shale and the Etchegoin and Paso Robles ("Tulare") formations, and the bearing of the relations between the Etchegoin and the Paso Robles on the occurrence of oil pools.

1917. McLaughlin, R. P., First Annual Report of the State Oil and Gas Supervisor: California State Min. Bur. Bull. 73.

Chapter 2 gives a description of conditions of water infiltration in the Belridge and Lost Hills fields as well as statistics of wells drilled, etc.

1918. McLaughlin, R. P., Second Annual Report State Oil and Gas Supervisor: California State Min. Bur. Bull. 82.

Gives statistics of wells drilled and a few notes on the progress of study of underground conditions.

1918. McLaughlin, R. P., Third Annual Report State Oil and Gas Supervisor: California State Min. Bur. Bull. 84.

GEOLOGY.

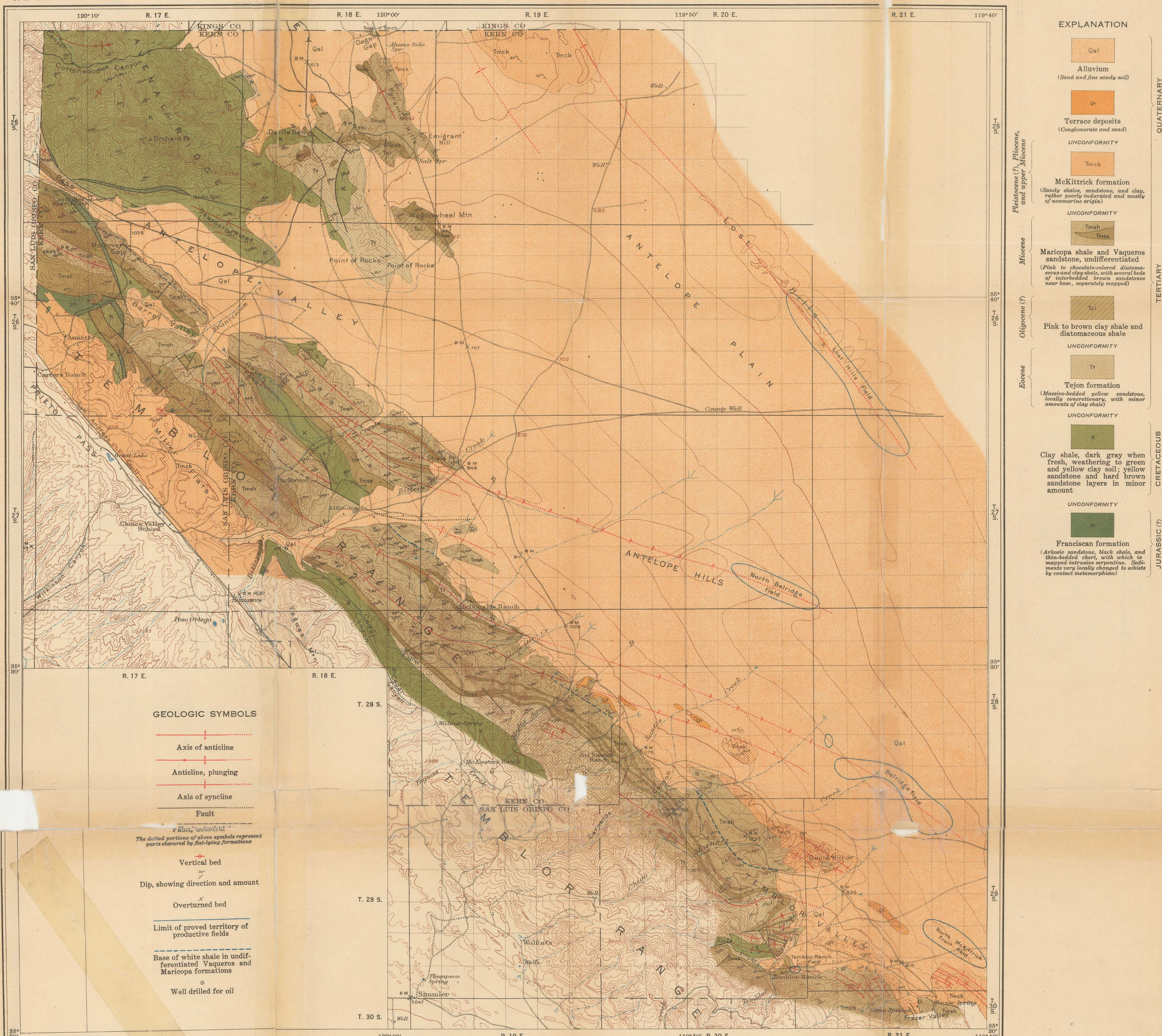
STRATIGRAPHY.

FRANCISCAN FORMATION AND ASSOCIATED IGNEOUS ROCKS (JURASSIC?).

The Franciscan formation, next to the oldest formation that outcrops in the Coast Range, consists of gray and greenish arkosic sandstone, dark and black fissile shale, and thin-bedded chert.[1] This formation has been generally assigned to the Jurassic on the basis of a few fossils found in it and its position beneath the Cretaceous. Basic igneous rocks have been intruded into the sedimentary beds in nearly all places where they are exposed. According to Fairbanks,[2] most of the intrusive rocks are of pre-Cretaceous age, but an in-

[1] A detailed study of the lithology and probable conditions of deposition of the Franciscan formation has recently been published by E. F. Davis, as California Univ. Dept. Geology Pub., vol. 11, Nos. 1 and 3, 1918.

[2] Fairbanks, H. W., U. S. Geol. Survey Geol. Atlas, San Luis folio (No. 101), 1904.



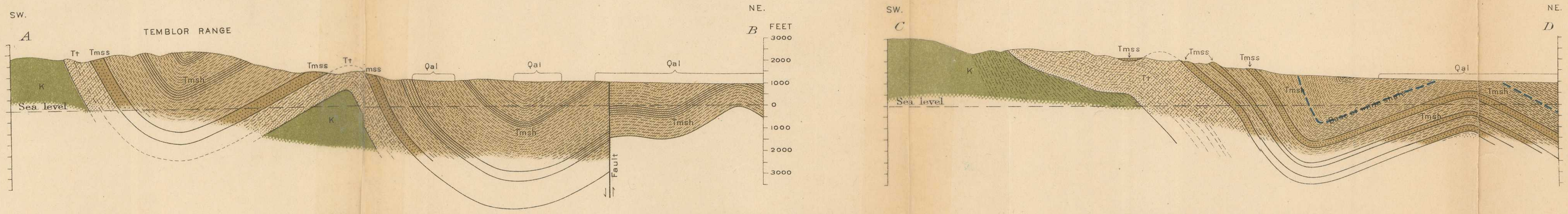
Base from parts of Lost Hills, Cholame, and McKittrick topographic maps

GEOLOGIC MAP AND SECTIONS OF NORTHWESTERN KERN COUNTY, CALIFORNIA

Geology by W. A. English assisted by W. S. W. Kew Surveyed in 1916

Scale 1/125000

Contour interval 100 feet.
Datum is mean sea level.



SECTION ALONG LINE A–B

Structure beneath alluvium, hypothetical

SECTION ALONG LINE C–D

Scale 1/62500

1921

trusive peridotite (usually altered to serpentine) is younger than the lower part of the Cretaceous. Local contact metamorphism has changed the Franciscan sedimentary rocks into schists that have considerable petrographic interest but that occupy very small areas. Because of the extremely intricate structure and the small size and irregular shape of many of the intrusive masses no attempt is made in this bulletin to differentiate the lithologic types in the Franciscan or to map the Franciscan separate from the associated rocks.

Within the area mapped (Pl. I) the outcrops of Franciscan rocks occupy small areas and are confined to the much-faulted district around the head of Antelope Valley. The fault-bounded strip of Franciscan rocks that extends southward from a locality west of the Antelope pump station consists mostly of peridotite and serpentine but also contains small areas of schist. In the northeastern part of sec. 8, T. 26 S., R. 17 E., is a rocky knob of what appears to be a metadiorite, with a marked schistose structure. A small area of limestone west of the Antelope pump station is described by Arnold and Johnson.[3] In sec. 16 there is an area consisting entirely of serpentine and farther south, close to the faulted anticlinal axis in the Vaqueros, there are several small areas of Franciscan which Arnold and Johnson describe in detail.

No oil is known to occur in Franciscan rocks, and their character and structure make it seem unlikely that oil will be found in them anywhere. Areas within which these rocks outcrop may therefore be safely considered as having no oil possibilities whatever.

CRETACEOUS ROCKS.

The Cretaceous rocks, which consist of dark marine clay shale with lenticular conglomerate and sandstone beds of considerable thickness, were deposited unconformably upon the Franciscan formation. Where the Cretaceous rocks are well exposed in the Coast Ranges, enormous stratigraphic thicknesses have been measured. West of Coalinga a thickness of 19,000 feet of mostly Lower Cretaceous beds is present[4] and north of Coalinga a thickness of 24,000 feet of Upper Cretaceous rocks.[5] The Cretaceous succession is in some areas broken by an unconformity which separates the Lower Cretaceous (Shasta series) from the overlying Upper Cretaceous (Chico formation). Elsewhere, as within the area here described, no unconformity has

[3] 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, p. 33, 1910.

[4] Pack, R. W., and English, W. A., Geology and oil prospects of Waltham, Priest, Bitterwater, and Peachtree valleys, Calif.; U. S. Geol. Survey Bull. 581, p. 127, 1915.

[5] Anderson, Robert, and Pack, R. W., Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, Calif.: U. S. Geol. Survey Bull. 603, p. 37, 1915.

been observed, and the separation, if made at all, must be made on the basis of fossils.

The field work for the present report was confined almost entirely to the areas that contain outcrops of Tertiary rocks that bear some relation to a study of the oil resources of the region. The Cretaceous was therefore only mapped where structural complications bring it to the surface within the areas of Tertiary formations that border the San Joaquin Valley. Outcrops of Cretaceous rocks were examined in a number of areas north of Bitterwater Creek and near the Temblor ranch. Most of Barril Valley is underlain by Cretaceous shale, good exposures of which are seen along the McGovern Gap road. Here, as at other places where the formation was examined, it consists of dark-green clay shale that contains intercalated beds of flaggy sandstone, most of them one-half to two inches thick, which make up perhaps 5 per cent of the stratigraphic thickness. The sandstone breaks up into plates, which weather to a dark reddish brown. These platy fragments, scattered over a surface covered by a clay soil, form reliable evidence of the presence of Cretaceous rocks. The soft clay shale is rather easily eroded, and Barril Valley is largely an erosional feature, determined by the presence of Cretaceous shale. Another area of lithologically similar Cretaceous rocks determines the low topography which extends southeastward from Raven Pass to Bitterwater Valley. The Cretaceous area on the north slope of Shale Hills contains some prominent beds of hard sandstone which weather to a reddish brown. These sandstone beds are 6 inches to 2 feet thick, and each bed is sharply separated from the interbedded shale, which even here makes up 80 per cent of the total thickness.

So far as known, the Cretaceous rocks within this area do not contain oil, except in very small quantities, and no seeps or other evidence of oil have been discovered. The presence of Cretaceous rocks at the surface should therefore discourage prospecting, and if penetrated in a well it should be abandoned, as it must have already passed all probable oil-bearing horizons.

TEJON FORMATION (EOCENE).

The Tejon formation, which unconformably overlies the Cretaceous rocks, is well represented in the central and southern part of the area mapped (Pl. I), where it consists of massive buff sandstone and less prominent dark clay shale. North of Bitterwater Creek it is absent, having been entirely eroded previous to the deposition of the Miocene rocks, which rest directly on the Cretaceous rocks. The massive cavernous-weathering quartzose sandstone is characteristic of the Tejon throughout the southern part of the State, and the formation was recognized within this area largely from its lithologic character and stratigraphic position.

The Tejon was examined along the McDonald anticline and in the higher hills from Agua Media Creek southward to the Temblor ranch. In the McDonald anticline the Eocene consists of interbedded dark-green shale and light-buff sandstone. Near the top of the section there is a massive yellow sandstone that contains a great many nearly round concretions from 2 to 3 feet in diameter. These concretions are very hard, and as the formation is eroded large numbers of them are left lying on the surface of the ground. The old sheep corral at the McDonald ranch is built of these concretions. A good example of the unconformity between the Tejon and the overlying Miocene beds may be seen along the northern end of the Tejon inlier in the McDonald anticline.

Farther back from the edge of the valley the Tejon is exposed in a continuous outcrop from a locality near Napoleon Spring southward to the Temblor ranch. The characteristic lithology makes this formation easily separable from the adjacent formations, and in many places clearly marked unconformities both at the base and top may be seen.

A paced section of the Tejon, measured along the ridge on the north side of Agua Media Creek, shows it to be approximately 1,800 feet thick, made up as follows:

Section of Tejon formation on north side of Agua Media Creek.

	Feet.
Top of section.	
Alternate sandstone and shaly sandstone and some shale; the sandstone beds weather to rather prominent craggy outcrops	400
Hard massive cavernous-weathering buff sandstone; contains irregular nodular concretions	100
Alternate sandstone and clay shale, comprising five zones of shale and four of sandstone; the shale is dark green to gray but not as dark as the Cretaceous shale	400
Concretionary zone, comprising mostly sandstone, together with some shale; contains hard round concretions 1 foot to 2 feet in diameter	250
Soft fine yellow shaly sandstone	100
Fine-grained yellow sandstone, shaly sandstone, and shale; the sandstone forms prominent outcrops on both sides of Agua Media Canyon	300
Soft fine-grained sandstone; weathers to a yellow and red soil	275
Base of section.	
	1, 825

South of Agua Media Creek the beds shown in the above section are present, and in addition about 1,000 feet of overlying buff sandstone, making a total thickness of 2,800 feet. The Tejon thins northward from Agua Media Creek. About a mile northeast of Walnut Springs it is only 1,000 feet thick, and a short distance northwest of Napoleon Spring it is entirely overlapped by the beds of the lower Miocene. Farther north, near the mouth of Cedar Canyon, the Tejon again appears as a massive sandstone, which is exposed for a distance of 2 miles along the strike and reaches a thickness of 400 feet.

The Tejon is well developed between Agua Media Creek and Temblor ranch and is composed of material similar to those in the section measured north of Agua Media Creek. Because of the unconformity at the base of the lower Miocene these beds rest on different beds of the Tejon in different places, including massive cavernous-weathering sandstone, nodular sandstone, and shaly beds.

The only fossils found in the Tejon south of Antelope Valley were the following forms from Salt Creek, which, however, are not characteristic:

Fossils from Tejon formation near Salt Creek.

Dentalium sp.?	Shark teeth.
Bryozoa.	Brachiopod.

The age determination rests on the lithologic similarity to the Tejon beds on the north side of Antelope Valley from Point of Rocks northward, where a good Tejon fauna is found near the base of the formation.

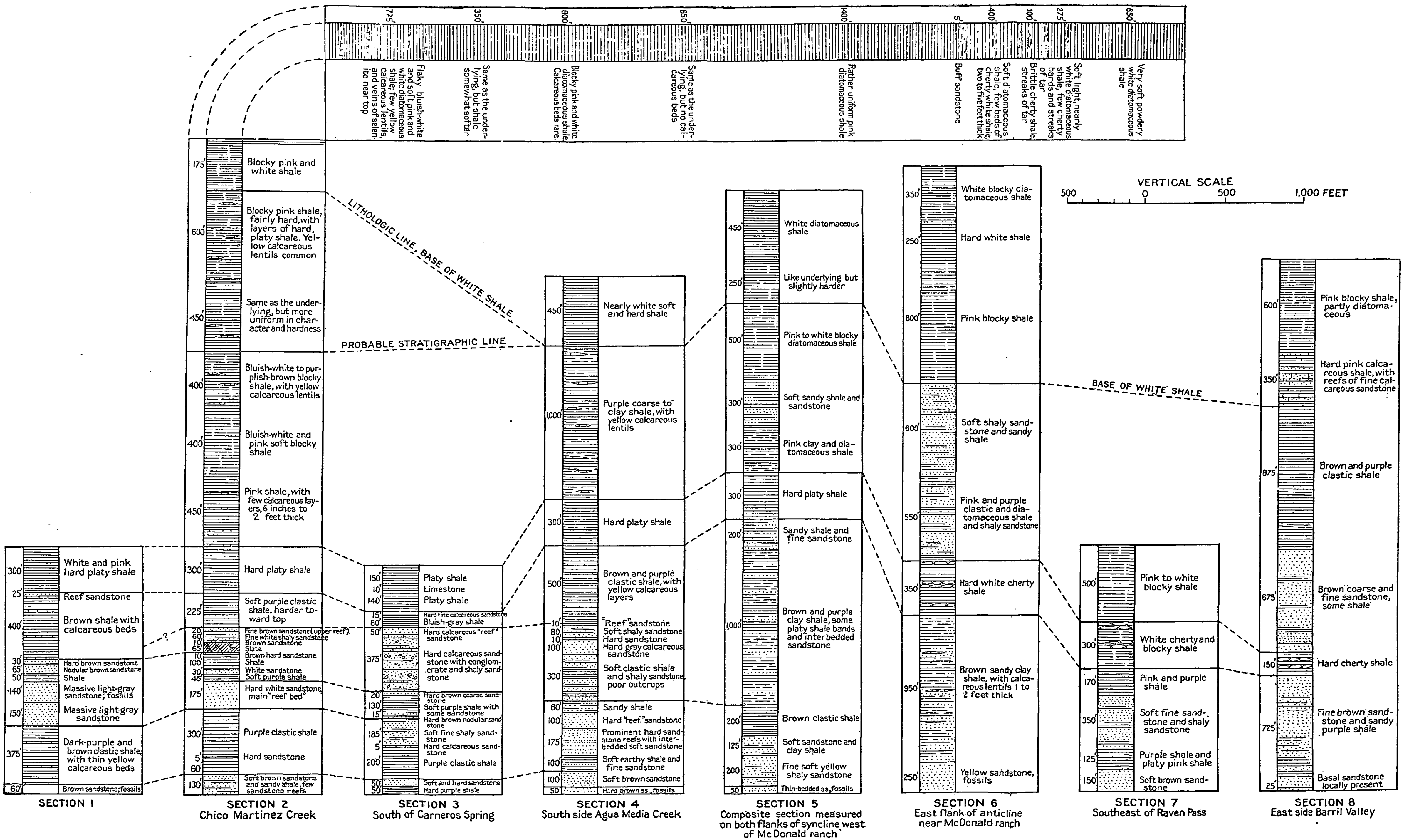
The Tejon is excellently exposed in the vicinity of Point of Rocks, on the north side of Antelope Valley. The writer made only a hasty examination of this area, a detailed description of which may be found elsewhere.[6] The beds consist of nodular, massive, and cavernous-weathering sandstone, similar to that which outcrops in the vicinity of Agua Media Creek. An excellent Tejon fauna was collected from hard calcareous sandstone beds near the base of the formation.

Like the other pre-Miocene formations within this area, the beds of Tejon age in all probability contain no oil. There are no seeps or other evidence of oil on the outcrop, and the absence of any diatomaceous shale in it or in older formations within this area makes the Tejon an unpromising formation in which to look for oil.

OLIGOCENE (?) ROCKS.

Rocks of possible Oligocene age crop out in the outer hills on the north side of Antelope Valley. The writer made only a very hasty examination of the region north of Point of Rocks and has fol-

[6] 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, pp. 38–39, 1910.



CORRELATION CHART SHOWING VARIATION OF VAQUEROS AND MARICOPA FORMATIONS ALONG STRIKE.

lowed the mapping of Arnold and Johnson, though with some modifications. According to their description,[7] the Oligocene (?) consists of about 1,800 feet of prevailingly pink and brownish weathering clay shale, at the base of which lies about 100 feet of nonnodular light-gray to buff sandstone inclosing a fossiliferous calcareous reef. The fossils found by them are not diagnostic of any particular horizon, and the tentative correlation of the beds with the Oligocene was based on their position below the reef zone of the Vaqueros. The writer believes that more detailed paleontologic and stratigraphic work may show that the Vaqueros, on the north side of Antelope Valley, which is mapped by Arnold and Johnson as only 15 to 150 feet thick, is really the equivalent of the top reef bed of the sections south of Devilwater Creek, and that the Oligocene (?) is the equivalent of the underlying part of the undifferentiated Vaqueros and Maricopa deposits, as shown in Plate II.

Arnold and Johnson describe an oil spring in sec. 23, T. 25 S., R. 15 E., in the Vaqueros-reef zone, and several shallow wells get a small amount of oil from the underlying shale, a short distance away. Farther north, in the Coalinga district, large amounts of oil are believed to have originated in Oligocene (?) beds, probably, in part at least, equivalent to these.

VAQUEROS SANDSTONE AND MARICOPA SHALE (MIOCENE).

GENERAL CHARACTER.

An apparently continuous series of marine sandstone and diatomaceous shale, containing lower Miocene fossils near the base, forms most of the foothills along the edge of the valley. This succession, which Arnold and Johnson in their report classified as undifferentiated Miocene, Vaqueros sandstone, Monterey shale, and Santa Margarita (?) formation is here treated as a single stratigraphic unit. It reaches a maximum thickness of more than 9,000 feet at Chico Martinez Creek, where a well-exposed section was measured (see Pl. II, sec. 2), and consists of interbedded sandstone and shale in the lower 1,500 feet, overlain by clay shale and diatomaceous shale. Much of the upper part of the shale is nearly white, of light specific gravity, and is made up in considerable part of the skeletons of diatoms and other skeletal fragments of minute organisms. According to the generally accepted theory, the oil found in this region originated in the diatomaceous shale and was formed from the soft parts of small organisms, the skeletons of some of which are present in the shale. The shale was not only the original source of the oil, but sandy beds in the shale formation form reservoirs from which many of the wells in the productive fields draw their supply of oil.

[7] Arnold, Ralph, and Johnson, H. R., op. cit., pp. 40–41.

These formations, therefore, bear a close relation to the oil, and they will be described in considerable detail.

Although the Vaqueros sandstone and the Maricopa shale are well exposed along the entire length of the foothills which border San Joaquin Valley, a nearly complete section is present only between Gould Hill and the mouth of Carneros Canyon. Even here the McKittrick formation rests in marked unconformity on the Maricopa shale, and a considerable thickness of the shale is undoubtedly overlapped and hidden from view by the McKittrick. The thickness of over 9,000 feet now exposed therefore represents a minimum original thickness, and the succession as originally deposited was probably much more than 10,000 feet thick. North and south of this locality the valley alluvium overlaps all the upper part of the series, and the study was necessarily confined to the lower beds.

The remarkable variation in lithology of these lower beds is graphically shown in the sections in Plate II. From Devilwater Creek southeastward a number of lenticular sandy beds are interbedded with the lower 1,200 feet of shale and sandy shale. Some of the zones of sandstones weather out prominently into reefs which may be seen for miles. The principal reef zones have been mapped as sandstone on Plate I. A closer examination shows that even these reef zones contain considerable amounts of interbedded shale and that the intervening shale zones contain less prominent thin sandy beds. The separation into sandstone and shale can not therefore be shown clearly on the geologic map. Above this reef-bed zone lies from 1,200 to 2,500 feet of pink to brown clay shale and diatomaceous shale, in the lower part of which is a prominent zone of hard platy shale and chert. These beds are overlain by light-colored to white shale, mostly diatomaceous, over 4,500 feet thick. The base of this upper shale zone is shown on the geologic map. The line of separation between this white shale and the underlying less diatomaceous shale is not sharp, and where, because of discontinuous outcrop, the line is not actually traceable the horizon shown as the base of the white shale may be wrongly placed, because of lithologic variation in the beds along the strike. In other words, the line shown as the base of the white shale for the area between Temblor Valley and Carneros Spring may not be at the same horizon as the lines shown near the mouth of Agua Media Creek and in Shale Hills. A comparison of the thickness of the measured sections suggests that the line drawn at the base of the white shale for the area south of Carneros Creek indicates a considerably higher horizon than the base of the white shale on Agua Media Creek. Such a correlation would place the base of the upper shale zone about 1,000 feet lower down in the Chico Martinez Creek section, and on the map the line would be at the western base of the prominent ridge in sec. 3 and of the 1,894-foot hill in sec. 10, instead of along their northeastern flank as shown.

The basal reef-bed zone is even more variable north of Devilwater Creek than south of it. From Devilwater Creek northward to Bitterwater Valley only a single zone of reef beds near the base of the section is present, and it ranges from 100 to 500 feet in thickness. North of Bitterwater Valley the lower sandstone is from 500 to 750 feet thick except in the McDonald anticline. In that fold there is an apparent thickness of nearly 2,000 feet in which sandstone beds are prominent. The structure along this part of the anticline is irregular and the mapping may not be entirely correct, so the apparent thickness may be due to duplication of beds by faults or folds or by the crushing and thickening incident to folding. If, as the writer believes, the thickness given represents the original thickness it is probably due to the sandy beds extending higher in the succession here, but there may be an extreme local thickening of the basal sandy zone, possibly due in part to overlap.

Farther north, on the northwest side of Barril Valley, a thickness of more than 3,000 feet of the lower sandstone was measured, and in this locality it appears that the sandstone beds are equivalent to all the beds below the horizon of the white shale as mapped in the hills east of Barril Valley and farther south.

CORRELATION AND AGE.

The classification of the beds of Vaqueros and later Miocene age has caused more disagreement among geologists than that of almost any other formations in the Coast Range. The reason for the disagreement lies in the fact that the succession of beds differs greatly within short distances and also in the difficulty in correlation by paleontology between the nonadjacent areas in which detailed work has been done. (See Pl. II.)

The beds here described as undifferentiated Vaqueros sandstone and Maricopa shale are believed to be equivalent in age to at least part of the Vaqueros sandstone, Salinas ("Monterey") shale, and Santa Margarita formation; but no unconformities or other basis for a division into these formations are present. Arnold and Johnson, who mapped in detail the area here discussed, divided this succession into four units—undifferentiated Miocene, Vaqueros sandstone, Monterey shale, and Santa Margarita (?) formation. No unconformities are described in their report as occurring between these formations, the separation being based on lithologic character or faunal content. The reasons for not following the classification of Arnold and Johnson may be summarized for each of their units as follows:

The fauna present in the undifferentiated Miocene beds, though it contains some species which are found in the so-called Oligocene beds of the Mount Diablo region, does not differ materially from the fauna in the overlying sandy beds mapped as Vaqueros by Arnold and Johnson. The overlap of the undifferentiated Miocene by Vaqueros indicated by Arnold and Johnson's mapping was not borne out by the present work. These basal beds and the overlying Vaqueros are lithologically similar and appear to have been deposited during a continuous cycle of deposition. Thus there appears to be no valid faunal, stratigraphic, or structural evidence for the separation of this lower unit within the area considered in this bulletin.

Arnold and Johnson's description of the Vaqueros sandstone does not state its structural relation to the overlying and underlying beds. Apparently no unconformity was found, and it was separated from the overlying "Monterey shale" because of its lithologic character. They say:

> Despite this [complex structure] the Vaqueros in its more intimate characteristics, as of palaeontology, lithology, color, thickness, etc., is quite uniform. It consists nearly everywhere of beds of tawny to brownish medium-grained sandstones, generally containing many fossils, and nearly everywhere calcareous. The beds are almost always resistant, and hence produce a characteristic reef topography, which alone is usually sufficient to distinguish the beds from any others in the region.[8]

This description, if warranted, would be a valid basis for separation. It is, however, not borne out by the writer's work or by Arnold and Johnson's detailed description of the Vaqueros or by their mapping. On their map the Vaqueros unit is used to show reef-like sandstone beds, irrespective of their stratigraphic position. Thus between Napoleon Spring and Temblor ranch there are two Vaqueros reefs, between which is "Monterey shale." Farther south, in the Midway district, a number of other Vaqueros reefs are shown in the "Monterey shale," and some even in the "Santa Margarita (?) shale." Their mapping therefore confirms the writer's conclusion that the lower or Vaqueros sandy zone grades upward into the "Monterey shale" and that there is no definite or even approximate boundary between the two which may be traced for any considerable distance. No unconformity has been found and no fossils have been found in the overlying shaly beds, so that it seems preferable to map the reef beds simply as sandstone phases in the undifferentiated Vaqueros and Maricopa.

The separation between the beds mapped as "Monterey shale" and "Santa Margarita (?) formation" is stated by Arnold and Johnson to be based mainly on the lithologic characters,[9] though they say that

[8] U. S. Geol. Survey Bull. 406, p. 43, 1910.
[9] Idem, pp. 55–56.

the "Santa Margarita" beds are locally unconformable on the "Monterey shale,"[10] and their areal mapping of the west side of Antelope Valley indicates a marked unconformity between the two. The writer has mapped a line at the base of the white shale which corresponds in a general way with the separation described by Arnold and Johnson, though differing materially in its location as mapped from the line at the base of their Santa Margarita (?) formation. No evidence of an unconformity at this horizon was found within the area studied, and the evidence is not regarded as sufficient to prove that this particular line marks the base of the beds equivalent in age to the Santa Margarita formation of the Salinas Valley region.

F. M. Anderson,[11] in his description of this region, has used the names "Temblor formation" for the lower sandy phase and "Monterey shale" for the overlying shale. As he did not publish a map, he was not under the necessity of showing the line of separation between the two formations. He believes that the "Temblor formation" is of the same age as the Vaqueros, but that the name "Temblor" should take precedence because of a supposed lack of definiteness in the original description of the Vaqueros. The name Vaqueros, however, has been adopted by the United States Geological Survey.

J. P. Smith[12] uses the name "Temblor" for the sandy beds at the base of the succession here described, but he believes on paleontologic evidence that they are younger than the Vaqueros sandstone as originally described and represent the time equivalent of the lower part of the Salinas shale ("Monterey shale") of the coast region, where it overlies the typical Vaqueros sandstone.

Thus there is a difference of opinion as to the relative ages of the beds here described and the Vaqueros sandstone and Salinas ("Monterey") shale of the coast region. Arnold's classification would place the basal beds in San Joaquin Valley (Oligocene (?) and undifferentiated Miocene) below the type Vaqueros; F. M. Anderson would have the sandstone formations in the two regions equivalent in age; and J. P. Smith would place the "Temblor formation" above the Vaqueros. The writer's view is that the Vaqueros sandstone in the two areas is roughly equivalent in age, and that during the submergence which began with the deposition of the Vaqueros and culminated with that of the Salinas shale each of many small areas was submerged at a slightly different time from the rest, so that the

[10] U. S. Geol. Survey Bull. 406, p. 63, 1910.

[11] Anderson, F. M., A stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 3d ser., Geology, vol. 2, pp. 156–248, 1905; a further stratigraphic study in the Mount Diablo Range of California: California Acad. Sci. Proc., 4th ser., vol. 3, pp. 1–40, 1908.

[12] Smith, J. P., Geologic range of Miocene invertebrate fossils of California: California Acad. Sci. Proc., vol. 3, pp. 161–182, 1912.

basal beds are not everywhere of the same age. However, the paleontologic work thus far done has not been sufficient to show which areas were first submerged.

LOCAL DETAILS.

In the following descriptions the area mapped is divided into seven districts, within each of which the character of the undifferentiated Vaqueros and Maricopa rocks is fairly uniform. These districts from south to north include (1) the area from McKittrick to the Temblor Ranch oil field, (2) the west side of Temblor Valley, (3) the area from Gould Hill northwestward to Carneros Creek, (4) the area from Carneros Creek to Devilwater Creek, (5) the area from Devilwater Creek to Bitterwater Valley, (6) the area from Bitterwater Valley northward to the head of Antelope Valley, and (7) the north side of Antelope Valley.

M'KITTRICK TO TEMBLOR RANCH OIL FIELD.

Within the area between McKittrick and the Temblor oil field the structure is extremely complicated, so that at most points the areal mapping can not show whether the outcropping beds represent the upper or lower part of the shale. All lithologic variations of shale occur from soft, powdery, poorly bedded white shale to hard, flinty material and chocolate-colored clay shale. In the vicinity of Sheep Springs several zones of shale breccia occur along fault zones. In this locality the harder of the thin beds of shale, one-half to 1 inch thick, are broken into angular fragments which are scattered through a matrix of softer shale. The formation looks like an angular conglomerate and resembles almost exactly certain phases of the McKittrick formation, for which it was apparently mistaken by Arnold and Johnson. On the ridge just south of Sheep Springs lie boulders of this material that have been hardened by local silicification to form a compact chert as hard as any found in the Franciscan formation. In the much faulted shale on the north side of Frazer Valley there are similar outcrops of shale breccia.

WEST SIDE OF TEMBLOR VALLEY.

The monocline along the edge of the hills farther north gives place to complicated structural features, consisting of small eastward-trending folds and faults along the west side of Temblor Valley. The basal 700 feet of Miocene beds exposed in this area is largely composed of sandstone, and these beds are overlain by a similar thickness of pink to chocolate-colored clay and impure diatomaceous shale. A hard calcareous sandstone, which forms the upper half of the sandy beds, weathers to prominent reefs. This reef bed wherever it was examined, both to the west of the Temblor ranch and to the east, where it swings around a small plunging anticline, is about 300 feet thick and consists of dark-brown to nearly white coarse sandstone and calcareous sandstone. The calcareous beds weather most prominently. They have a pitted appearance, and here and there a concretionary nodule stands out in them. Much of the light-colored sandstone is cross-bedded, and an especially good example of cross-bedding is shown in the reef on the north side of the small syncline in the SE. ¼ sec. 23, T. 29 S., R. 20 E. Below this reef bed lie softer sandstone and shale. Toward the south these lower beds are more sandy, and a basal sandstone zone has been mapped. West of Temblor ranch they consist of brown to dark-gray sandstone and shaly sandstone, in which the bedding planes are not very distinct. Northward from the south line of sec. 23 these beds below the prominent reef bed are less sandy and consist largely of dark shale, which in some places contains fossiliferous sandy beds from 5 to 20 feet thick.

GOULD HILL TO AGUA MEDIA CREEK.

Within the area between Gould Hill and Agua Media Creek the section of the Vaqueros and Maricopa formations that is exposed is by far the most complete section that has been measured anywhere within the region. The beds, which dip 45°–70° NE., contain no minor folds and are excellently exposed. The following section is also shown graphically as No. 2 on Plate II:

Section of Vaqueros and Maricopa formations at Chico Martinez Creek.

Top of section.	Feet.
Very soft, light, porous, nearly white diatomaceous shale	650
Soft white diatomaceous shale, containing three or four hard cherty layers 1 to 5 feet thick in which some tar is present	275
Hard nearly white cherty shale, considerably crushed and breaking into small angular fragments whose interstices contain tar and solid bitumen, makes up half the thickness and softer pink shale the other half	100
Medium-indurated pink shale, which breaks into large angular and discoidal fragments, not very fissile	400
Brown sandstone	5
Medium-indurated pink shale, rather uniform in character, containing yellow calcareous beds 6 inches to 1 foot thick at intervals of 20 to 100 feet	1,405
Pink shale, weathers white, like the overlying shale but contains no calcareous beds	650
Pink blocky shale; calcareous beds rare	800
Interbedded soft blocky shale and a harder shale that breaks into thin flakes; calcareous lentils 20 to 50 feet apart	350
Flaky bluish-white shale and softer pink blocky shale, with interbedded calcareous lentils 20 to 40 feet apart. A pit at the top of this shale exposes a 3-inch vein of selenite in the shale; the prismatic crystals are perpendicular to the sides of the vein, which in turn is parallel to the bedding. Several other veins of selenite in the next 100 feet of overlying shale	775

	Feet.
Soft pink blocky shale, which together with all overlying beds is more or less diatomaceous; it forms the base of the upper shale division	175
Gray clastic shale; weathers yellow to pink and contains interbedded layers of hard white platy shale, which cause the beds of this zone to weather to ridges; yellow calcareous beds are numerous	950
Gray clastic shale; weathers to bluish white and purplish brown and breaks into small crumbly fragments; no calcareous beds	400
Soft brownish, purple-weathering clastic shale; contains few calcareous lentils	450
Hard shale zone, comprising hard white platy shale and calcareous shale, interbedded with softer clay shale	300
Soft yellow clay soil, probably derived from clastic shale	225
Hard brown and white sandstone (upper reef)	20
Fine white shaly sandstone	60
Hard sandstone	10
Shale	65
Hard brown sandstone	10
Brown-weathering clastic shale	100
White sandstone, fairly resistant reef	30
Soft purple clastic shale	45
Hard white resistant sandstone; main reef bed	175
Shaly beds comprising purple clastic and slightly diatomaceous shale and soft shaly sandstone	300
Hard calcareous fossiliferous reef	5
Purple clastic shale	60
Soft brown sandstone and sandy shale, containing a few thin beds of hard sandstone	130
	8,920

In the reef-bed zone the lower of the two reefs is by far the most prominent bed. It reaches a maximum thickness of 250 to 300 feet and consists almost entirely of hard gray calcareous sandstone, in which fossil fragments are common. Below this reef are much thinner, less prominent reefs, each of which is traceable for only a short distance. The basal beds carry abundant well-preserved fossils, and a large fauna could undoubtedly be obtained from these beds by persistent collecting, especially in the vicinity of Carneros Springs and farther north, near Agua Media Creek.

The unconformity between the Miocene and the underlying Tejon is very striking in this area. Northwestward from the saddle in the northwest corner of sec. 15, T. 29 S., R. 20 E., the Tejon is seen to be overturned. It dips 70°–90° SW., but the dip changes abruptly to northeast at the base of the Miocene. Along the contact the Miocene rests on different phases of the Tejon, at one place massive sandstone and at other sandy shale and nodular sandstone.

CARNEROS CREEK TO DEVILWATER CREEK.

Within the area between Carneros Creek and Devilwater Creek there are three main reef zones besides a less prominent basal sandstone. The sandstone zones range from 50 to 300 feet in thickness, but the most prominent part of each reef is thinner, usually not over 25 to 50 feet in thickness. The reefs form long, narrow, dark ridges with broad slopes along the dip from which the overlying softer shale has been stripped by erosion. Their appearance is particularly striking near the mouth of Santos Creek, where because of some minor folding and faulting they form a veritable maze. The reef beds are separated by sandy shale and clay shale, the latter generally dark gray when fresh and weathering to purplish brown or dark yellow. Above the reef zone lie beds of dark clay shale, including a few hard yellow calcareous lenticular beds, and above this dark shale comes the white shale division. Within the clay shale there is a zone of hard yellow platy shale, which lies from 100 to 500 feet above the upper reef and is 150 to 250 feet thick. Near Carneros Creek this zone is not very prominent and is represented by a 20-foot bed of hard calcareous shale, but to the north this shale becomes thicker and more resistant, and near Devilwater Creek it outcrops even more prominently than the sandstone reef beds themselves.

The separation between the white diatomaceous shale and the underlying clay shale is much more distinct near the mouth of Agua Media Creek than in the area southeast of Carneros Creek. The upper shale is nearly white and mostly hard and cherty, breaking into small angular blocks, some of which are sufficiently silicified to have a resinous luster. The greater silicification of this shale as compared to that in the section along Chico Martinez Creek is probably due to the greater amount of folding and crushing to which it has been subjected. The upper shale in the small area in sec. 13, T. 28 S., R. 19 E., on the northeast side of the syncline is less disturbed and also softer and more porous.

DEVILWATER CREEK TO BITTERWATER VALLEY.

Northward from Devilwater Creek the upper reef beds become much less prominent and grade into sandy shale. The hard cherty zone which overlies the upper reef becomes much more prominent than it is farther south, and a zone of shaly sandstone appears above the cherty zone.

This lack of prominent reef beds is particularly noticeable in the McDonald anticline, in which only the basal 50 feet of the Miocene weathers out prominently. This lower bed is made up of calcareous fossiliferous reefs, each only a few feet thick, separated by shaly sandstone. Where the Vaqueros swings around the axis of the anticline in sec. 31, T. 27 S., R. 19 E., the basal beds contain, besides many large oysters and other Vaqueros fossils, a number of hard round concretions from the underlying Tejon, which are fairly honeycombed with holes made by boring mollusks. Above the hard sandstone lie about 150 feet of softer yellow sandstone, with some interbedded clay shale, and these two sandstones make up the sandstone zone as mapped. From the head of Devilwater Creek northwestward a basal zone 500 to 600 feet thick has been mapped as sandstone. A hard sandstone reef from 25 to 100 feet thick, a continuation of the lower reef in the area to the southeast, forms the top of this lower sandstone phase. Below the reef lies brown-weathering clay shale, with which a few reef beds 5 to 20 feet thick are interbedded. The following two sections give an idea of these lower beds:

Section in northeastern part of sec. 34, T. 27 S., R. 18 E.

	Feet.
Hard brown calcareous sandstone	20
Soft brown sandy shale and sandstone, with a few thin reef sandstone beds	400
Massive white quartzose sandstone, in part calcareous	100
Unconformity.	
Cretaceous shale.	

Section on east side of mouth of Cedar Canyon.

	Feet.
Hard brown fossiliferous reef, composed of calcareous sandstone	10
Soft brown sandy shale	150
Hard brown reef, composed of calcareous sandstone, with fossils	20
Soft brown clay shale, containing a few thin beds of sandstone	350
Brown sandstone	20
Unconformity.	
Massive yellow Tejon sandstone.	

Above the lower sandy zone lies from 1,000 to 1,200 feet of clay shale, in which lenticular concretionary beds of yellow calcareous shale from 6 inches to 2 feet thick are numerous. These beds are well exposed in the southeast flank of the syncline in the Miocene beds. Above the clay shale zone comes 300 to 350 feet of hard platy shale, which forms a series of prominent knobs, trending northwestward from the 2,923-foot hill in sec. 7, T. 28 S., R. 19 E. By means of this hard-shale zone on the two sides of the closely appressed syncline this fold may be traced for 2 miles south of Bitterwater Valley, but farther south the hard shale does not form sufficiently prominent outcrops to be traceable along the east flank of the syncline. The resistance of this shale to erosion is due to the presence of beds 1 inch to 3 inches thick composed of light-yellow hard platy porcelaneous shale interbedded with an equal amount of softer clay shale. Northeast of the McDonald anticline this hard shale is somewhat different in character. It becomes in this area a more uniform hard white shale, which breaks into small blocky fragments whose surfaces have a resinous luster. Above the hard shale lies a zone of soft brown sandy shale that contains some shaly sandstone. This sandy shale forms a well-defined belt of low topography in the hills south of the mouth of Bitterwater Valley, and the axis of the syncline for about 2 miles south of Bitterwater Valley is formed by these beds. Above the sandy zone lies the white shale division, which is well exposed on the northeast flank of the McDonald anticline, where much of the material is soft and porous, like the upper part of the shale in the section on Chico Martinez Creek. The white shale also outcrops in the axis of the syncline in the high hills southwest of McDonald ranch.

BITTERWATER VALLEY NORTHWARD TO HEAD OF ANTELOPE VALLEY.

The structure in the area north of Bitterwater Valley is considerably more complicated than that farther south, and for this reason it is somewhat difficult to determine the stratigraphic relations between adjacent beds. There is also a puzzling divergence in character between the beds along the northward continuation of the McDonald anticline and those to the northeast, in the outer hills. This difference in lithologic character appears to be particularly striking on a first examination. The Miocene beds, which rest on the Cretaceous on both sides of the valley southeast of Raven Pass, consist in large part of a nearly white blocky diatomaceous shale, in which very little sandstone or clay shale is noticeable, except in the basal sandy zone, which is probably not more than 500 feet thick. In contrast to this succession of beds is that which lies between the McDonald anticline and the syncline to the east, where the 1,500 to 2,000 feet of beds that are exposed along the axis of the anticline include purple clay shale, alternating with hard calcareous reef-forming sandstone beds and softer brown shaly sandstone, and above the lower reef-bed zone a zone of purple clay shale, containing yellow calcareous lentils, at least 1,000 feet thick and considerably thicker if the section along the ridge north of Bitterwater Valley on the east side of the McDonald anticline is not duplicated by faulting or folding. This discrepancy in lithology led Arnold and Johnson to believe that there is an upper white shale (Santa Margarita(?) formation) which overlaps the lower shale and sandstone ("Monterey" and Vaqueros).

After a careful examination the writer came to the conclusion that the basal beds in both areas were deposited at approximately the same time, even though they differ much in character. The tendency of the beds farther east to be whiter and more diatomaceous is also notable on the two flanks of the McDonald anticline south of Bitterwater Valley. The sandy beds, which overlie clay shale as exposed near Packwoods, do not differ greatly from the beds near the head of Devilwater Creek, where many prominent sandstone reefs are present in the lower 1,500 feet. The same succession of sandstone and soft and hard shale is present in the shale hills as in the area south of the mouth of Bitterwater Valley. The lower 500 feet of beds in the shale hills consist chiefly of sandstone, though they do not weather to prominent outcrops, and fragments of shale derived from the interbedded hard shale give the soil a shaly appearance. Locally the sandstone is indurated and forms small buttes of a hard calcareous sandstone. Hard sandstone of this type was noted at Shale Point, near the east line of the SE. ¼ sec. 1, T. 27 S., R. 18 E.; about 1,500 feet south of the northwest corner of sec. 12, T. 27 S., R. 18 E.; and about 1,000 feet west of the Twisselman ranch buildings in sec. 14, T. 27 S., R. 18 E. In each of these localities the hard sandstone is traceable into soft sandstone that weathers less conspicuously, the local prominence being due entirely to an exceptional amount of induration. Above the basal zone of sandstone is a medium-indurated white diatomaceous and clayey shale, which ranges from 200 to 600 feet in thickness. The shale weathers to blocky and hackly prismatic fragments and contains interbedded buff calcareous shale lentils. This zone corresponds to the purple clay shale zone elsewhere and is overlain by hard white diatomaceous shale and sandy shale. Thus the same succession is present in the shale hills as elsewhere, though the beds as a whole are much lighter in color and more diatomaceous.

Another example of extreme lithologic variation within a short distance is the change in character of the Vaqueros formation and Maricopa shale between the hills east of Barril Valley and the syncline which trends northwest across sec. 8, T. 26 S., R. 17 E. The character of this change is illustrated by the following section and by No. 8 of the graphic sections on Plate II:

Section of Vaqueros sandstone, measured across sec. 6, T. 22 S., R. 17 E., near head of Antelope Valley.

Top of section.	Feet.
Buff-weathering quartzose sandstone containing reef-like beds 5 to 20 feet thick	100
Soft shaly sandstone and sandy shale; weathers to yellow loam	1,400
Quartzose buff-weathering sandstone, alternating hard and soft, the hard beds locally forming extremely rugged reef outcrops; contains *Turritella ocoyana* at base	1,800
Shale and sandstone, the shale largely derived from Cretaceous material	300
Base of section.	
	3,600

The lower 1,575 feet of beds in the area east of Barril Valley corresponds to the lower 2,100 feet of mostly massive quartzose sandstone in sec. 6. The next 1,225 feet of prevailingly shaly beds in the area east of Barril Valley corresponds to the 1,500 feet of sandstone and sandy shale in sec. 6. Thus, in a distance of only a few miles a succession of shales that contain a small amount of sandstone changes to massive coarse sandstone and shaly sandstone. Above the 3,600 feet of sandy beds in the syncline lies pink diatomaceous shale, which corresponds with the upper white shale division in the hills that flank the San Joaquin Valley.

NORTH SIDE OF ANTELOPE VALLEY.

The mapping of the north side of Antelope Valley is almost entirely copied from Arnold and Johnson, though with some modifications. According to their mapping, the post-Tejon formations include Oligocene (?), undifferentiated Miocene, Vaqueros, and Santa Margarita (?) formations. These beds are shown in this bulletin (Pl. I) as Oligocene (?) and sandstone and shale phases of the undifferentiated Vaqueros sandstone and Maricopa shale. The undifferentiated Miocene mapped by Arnold and Johnson is included with the overlying Vaqueros and Maricopa shale.

According to Arnold and Johnson, the Vaqueros consists of 15 to 150 feet of calcareous sandstone, much of which is fossiliferous. It is overlain by pink and white, more or less diatomaceous shale in which there is very little interbedded sandstone or sandy shale. The underlying undifferentiated Miocene is not described by them.

SANDSTONE DIKES.

Dikes of sandstone were noted in the shale at two places. A sandstone dike 100 feet wide and several hundred feet long trends northeastward across the top of the hill just east of the center of sec. 5, T. 27 S., R. 18 E., cutting the shale nearly at right angles to the bedding. The dike consists of a hard, somewhat conglomeratic sandstone and is irregularly stained along the joint planes. Three small parallel dikes traverse the west slope of the prominent ridge near the south line of sec. 3, T. 29 S., R. 20 E., on the north side of Chico Martinez Creek. The sand that formed the sandstone in the dikes is supposed to have been squeezed into its present position along faults in the shale while it was still in a plastic condition.

Another peculiar effect of pressure is shown in the area that lies northwest across Carneros Creek from the prominent hill in the NE. ¼ sec. 31, T. 28 S., R. 20 E. In this locality a hard sandstone reef, which dips 80° NE., is exposed in the middle of a succession of clay shale beds which dip only 20°. This hard bed resembles the sandstone dikes in that its sides are not parallel to the bedding in the adjacent shaly beds. This sandstone, however, shows bedding and was evidently forced up through the shales as a rigid mass during the folding of the beds.

RELATION TO PETROLEUM.

The oil found in the fields along the edge of San Joaquin Valley south of Coalinga is believed to have had its origin in the diatomaceous shale of the Vaqueros and Maricopa formations, the wells getting their supply of petroleum from the overlying sandy beds and also from sandstone lenses in the shale. It is therefore necessary to determine whether the shale underlies an area to be prospected and at what depth it would be reached in drilling. Its recognition in well logs as brown or gray shale gives a useful datum for the correlation of strata between wells, though because of the unconformity at the base of the overlying beds the sands within the shale may not be parallel to its plane of contact with the overlying (McKittrick) formation.

McKITTRICK FORMATION (UPPER MIOCENE, PLIOCENE, AND PLEISTOCENE ?).

Overlying the Maricopa shale is a formation of marine and fresh-water sand, clay, and gravel to which the name McKittrick formation was applied by Arnold and Johnson. These beds largely represent the time equivalent of the Paso Robles ("Tulare") formation of the Coalinga area but include some marine beds toward the base that are probably equivalent to part of the Etchegoin formation. These beds of Etchegoin age crop out only in a very small area and were mapped with the overlying beds of Paso Robles age, though, as shown by Gester, there is an unconformity between the Etchegoin and Paso Robles beds in the region immediately adjacent to the southeast.[13] The relation of the Etchegoin to the Paso Robles is of considerable significance in determining the likelihood of obtaining oil in this region, as most of the oil in the developed fields to the south is produced from the Etchegoin formation. The beds described in this bulletin as McKittrick are assumed to be of Paso Robles age unless it is specifically stated otherwise.

The almost entire absence of rocks of Jacalitos and Etchegoin age from the surface within this region and their comparative thinness where they are penetrated in drilling are significant. In the Lost Hills and Belridge fields beds carrying marine fossils of probable Etchegoin age are penetrated in the wells, but their comparative thinness allows the oil sands, which lie directly above the

[13] Gester, G. C., Geology of a portion of the McKittrick district: California Acad. Sci. Proc., 4th ser., vol. 7, No. 4, 1917.

Maricopa shale, to be reached at a relatively shallow depth. If the same stratigraphic thickness of Jacalitos and Etchegoin rocks were present in these fields as is found in Kettleman Hills the oil sands would lie at an unattainable depth. Before any drilling was done the failure to recognize that the stratigraphic succession in these fields might be the same as that exposed in Gould Hill, rather than like that in Kettleman Hills, led geologists to regard the Lost Hills as probably very deep territory. The Etchegoin is likewise thin in the North Belridge field and is apparently not developed to anything like its maximum thickness anywhere in this region. Its presence beneath the outcropping Paso Robles beds adds uncertainty to predictions of drilling depths in untested areas, as its thinness is probably due in part at least to erosion in pre-Paso Robles time, and the amount of erosion may have been entirely different at points comparatively close together. The unconformity must also be considered in comparing the structure in the Paso Robles at the surface with the structure in the oil sands as determined by a study of well logs.

The separation of the McKittrick formation and the overlying terrace beds is in many places difficult because of the lithologic similarity between the two, particularly in areas like the Antelope Hills, where outcrops are poor and the character of the soil is about the only evidence available. In sec. 29, T. 29 S., R. 21 E., an unconformity is present between some flat-lying gravel and boulder beds which cap several hilltops and the underlying McKittrick, and an unconformity is probably present in most places between the McKittrick and the terrace deposits.

The lithologic character of the McKittrick formation is well shown in the hills of the McKittrick Front, on the northeast side of McKittrick Valley, though the numerous small folds make it impossible to establish the sequence of beds for any considerable stratigraphic thickness. The formation as a whole is soft and contains gray clay shale, sandy clay, fine and coarse white, yellow, and brown sandstone, and shale pebble conglomerate. Locally a hard white limestone bed occurs in the clays, and a few of the thinner sandstones are fairly well indurated. Of the lithologic types present the soft gray sandy shale and the fine-grained shaly sandstones are the most abundant and form over 80 per cent of the total thickness of beds exposed. At a number of places the outcropping sands are richly impregnated with oil. The oil is confined to the coarser beds, and two oil sands may be separated by a parting of shale in which there is no evidence of oil.

From Fraser Spring northward to Temblor Valley the McKittrick is poorly exposed and its separation from the terrace gravels is difficult. A line of springs occurs along its contact with the Maricopa shale in sec. 33, T. 29 S., R. 21 E., and this contact, which is not well exposed, may possibly be a fault.

In Gould Hill and to the northwest the exposures of the McKittrick are fair, especially its basal beds, but the structure is complicated by small folds that make it difficult to measure more than fragmentary sections. The basal McKittrick is well exposed in a small gulch that trends northward across the eastern part of the area of Maricopa shale in sec. 7, T. 29 S., R. 21 E. The basal bed is a massive fossiliferous conglomerate that contains shale pebbles in a hard white limy matrix. This bed is about 10 feet thick and is overlain by 30 to 40 feet of soft white and pink sands and shaly sand. Above these beds lie beds of brown and gray clays and sands. Just at the edge of the valley a bed of shale-pebble conglomerate, considerably silicified, forms the crest of several small hills. The basal bed in this section is probably of Etchegoin age. The McKittrick is also well exposed on the west side of the small hill in the SE. ¼ sec. 2, T. 29 S., R. 20 E., just south of Chico Martinez Creek. The basal 50 feet at this place consists of a light-gray porous gravel bed made up of rounded pebbles a quarter of an inch to 2 inches in diameter, of quartzite, slate, and white shale and a very few of granite. This gravel bed is overlain by soft white poorly bedded shale in which are scattered fragments of yellow calcareous shale. All this reworked material has been derived from the Maricopa shale, and this phase of the McKittrick presents nearly the same appearance as poor outcrops of the shale. One point of difference is that on a soil-covered slope underlain by the Maricopa shale the calcareous fragments tend to be most numerous along lines parallel to the beds from which they were derived, whereas in the McKittrick they are scattered at random over the surface. The same succession is traceable northward to sec. 34, where the hill in the south-central part of the section is formed of reworked diatomaceous shale, and the lower beds, which dip 20°, as recorded on the map, are shale-pebble conglomerate.

The low hills that lie mostly in sec. 27 furnish some of the best outcrops of the McKittrick. The dip is 30°–40° NE., and more than 1,500 feet of beds are exposed. Most of the beds are white clay shale, largely made up of reworked material from the Maricopa shale, and these beds give the hills a whiter appearance than the surrounding areas of terrace material. On the southwest slope of the ridge there are several limy sandstone beds, which contain marine (upper Etchegoin?) fossils. Several hundred feet farther east, at the point where the dip of 40° is recorded on the map, there is a conglomerate 5 feet thick composed of well-rounded granitic boulders in a matrix of pure white quartzose sand. Above this conglomerate lie soft gray and white clayey and shaly beds, most of which do not furnish good outcrops.

In both Antelope Hills and Lost Hills the McKittrick formation reaches the surface, but over most of the area it is difficult to determine whether the brown pebbly soil is derived from the McKittrick or from an overlying terrace formation. In the Antelope Hills most of the surface soil is probably derived from terrace gravels, but a fine powdery white sand, which is exposed in a pit on the Belridge property, in sec. 35, apparently belongs to the McKittrick formation. At the Belridge camp, in the southeastern part of sec. 35, one of the houses is built on a small mound composed of a brown and white speckled sandstone, which belongs either to the McKittrick or more probably to the terrace gravels. The white specks in the sand are hard bits of diatomaceous shale. Sandstone of the same character caps the terrace deposits which form the low hills in sec. 21, T. 28 S., R. 29 E., a few miles to the southwest.

Gray shale of the McKittrick is exposed at a number of points in the northern part of the Lost Hills, where small cuts have been made. Terrace gravels also form the surface over part of the hills, and at most points it is impossible to tell whether the surface soil is derived from underlying McKittrick beds or from the terrace formation. Locally the surface material has been hardened by a superficial deposit of gypsum, and care must be exercised not to mistake this material for the McKittrick.

QUATERNARY SAND AND GRAVEL.

At the end of the period of deposition of the McKittrick formation and during the later part of that period, there was a general folding and uplift of the rocks of this region, and thereafter the history of the Coast Ranges is one of erosion rather than of deposition, so that Quaternary deposits are comparatively thin and insignificant within the area of the recent mountains. The San Joaquin Valley, on the other hand, is supposed to be a geosyncline and to have been the site of deposition of a large quantity of Quaternary gravels. Both the Sierra Nevada and the Coast Ranges were uplifted near the beginning of Quaternary time, and together they are supposed to have furnished the material for a Quaternary formation which has been estimated to have a thickness in the center of the valley of several thousand feet, some estimates being as high as 10,000 feet. Any such thickness of Quaternary deposits would put the oil-bearing beds entirely out of reach of the drill. Despite this supposed thickness in the center of the valley, the Quaternary gravels are only a few feet thick in the Lost Hills, which are topographically rather far out in the valley. These hills, however, might be regarded as a part of the area of uplift rather than of the geosyncline, but the writer is not convinced that there may not be other areas even farther out in the valley in which the thickness of Quaternary gravels is small.

At some time during the Quaternary period a surface that presented less relief than the present surface was established along the valley slope of the Temblor Range. Gravels were deposited to a thickness of at least 50 feet on this surface, which now lies about 300 feet above the valley level. Only a very few patches of gravel that occupy isolated hilltops have escaped erosion. Other Quaternary deposits, which were laid down when the level of the west side of the valley was slightly higher than at present, form the low hills that lie mostly in secs. 18, 20, and 21, T. 28 S., R. 20 E. These hills are formed of soft brown-weathering sand considerably finer grained than the valley fill now being deposited.

STRUCTURE.

GENERAL FEATURES.

The discussion of the structure of this region may appropriately be divided into two parts—first, the structure of the Diablo and Temblor ranges, in which the Tertiary and older formations outcrop and within which the structure has been worked out in considerable detail, and second, that of the area covered by Quaternary valley fill, within which much of the structure of the underlying Tertiary beds may only be surmised. Within this area covered by the valley fill, if anywhere, future prospecting is likely to disclose the presence of new productive oil pools, and the structure of the hills is chiefly significant with regard to the oil prospects of the region because it furnishes a clue to the conditions beneath the valley floor.

The broad, nearly level surface of the valley alluvium may be regarded much as if it were an extensive lake, concealing the underlying Tertiary formations up to a certain level of elevation, and not as a line marking a separation between two different types of structure. Though the valley is generally supposed to be determined by a geosyncline and the hills by uplift in post-McKittrick time, the edge of the hills does not everywhere coincide with a structural line separating two such major structural features. During late Quaternary time the western limit of the valley fill has not marked a structural line but has steadily extended farther and farther west, its location at any particular geologic time being dependent upon the amount of deposition of Quaternary gravels which had taken place. Thus, early in the Quaternary period the Tertiary beds were probably exposed far out in the present valley, and in the geologic future the Quaternary deposits may extend far up toward the crest of the present Coast Ranges, obscuring much of the structure which may now be seen. The Tertiary structure, however, remains approximately unaltered, and the location of the western limit of valley alluvium depends as much on Quaternary deposition as on Tertiary structure.

STRUCTURE OF DIABLO AND TEMBLOR RANGES.

Most of the smaller structural features within the area mapped are clearly shown on the geologic map (Pl. I) and need not be described in detail. The following descriptions are therefore confined to the larger structural features and to those smaller features that are of particular interest because of their connection with the accumulation of oil or for other reasons.

The hilly and mountainous region between San Joaquin Valley and the sea is known as the southern Coast Ranges. Individual ranges, more or less distinctly separated from the ranges on either side by intervening wide valleys, may be recognized within this region. These ranges and valleys had a structural origin, having been uplifted or depressed to their present relative positions at the end of the McKittrick epoch. That is to say, the ranges owe their present topographic elevation to the uplift, and if the term used to describe an analogous origin of features of drainage may be applied to them they should be called consequent ranges. Many of the component ridges and other features of the present topography are due, however, to differential erosion acting on rocks of differing resistance. Though they are due to uplift, it is hardly correct to say that all the ranges are anticlinal, for the post-McKittrick uplift that formed them was only one of many uplifts that affected the Tertiary beds, and in some places the latest uplift has elevated a previously formed syncline or a block containing complicated folded and faulted structure and thus formed one of the present ranges. Parts of two of these recently uplifted ranges lie within the area mapped. The mountains north of Antelope Valley form the southern terminus of the Diablo Range, and the hills southwest of Antelope Valley are situated on the northeast flank of the Temblor Range.

The lines of geologic structure within these ranges trend northwest and are therefore roughly parallel to the ranges. The individual folds within each range are not, however, exactly parallel to it but trend more nearly west. Some of the individual anticlines have a tendency to extend out into San Joaquin Valley, where they determine low, more or less completely buried groups of hills similar to the ranges to the west but smaller, less intensely folded, and not faulted to any extent. Thus the Lost Hills anticline and its northern continuation in Kettleman Hills and the parallel Kettleman Plains syncline form an eastward repetition of the structural features of the ranges to the west. The folding, however, is less intense, and the formations are younger, indicating a decrease in intensity of both folding and uplift toward the east. The smaller original uplift toward the east has been a considerable factor in determining the edge of the present valley, though, as has been pointed out, it has not been the only factor, and the edge of the valley does not everywhere follow the lines of this change. As most of the productive oil fields have been developed in the belt of these low folds that parallel the Coast Ranges on the east, the chief aim of the present work is to determine their location and character.

STRUCTURE OF THE AREA INCLUDED IN SAN JOAQUIN VALLEY.

The Quaternary valley fill extends farther west, relative to the structure of the Tertiary rocks, in the region around Antelope Valley than in the region to the north or south. In the Coalinga region, to the north, the Kettleman Hills, which are determined by an anticlinal fold, rise well above the level of the valley. South of the Kettleman Hills, however, the Quaternary deposits have almost completely buried the continuation of this anticline in Lost Hills, as well as the Antelope Hills anticline and the eastward continuation of the McDonald anticline. In Antelope Valley the alluvium extends westward well within the area of folded and faulted beds which are characteristic of the mountainous parts of the Coast Ranges. To the south of this area the low outlying folds in Elk and Buena Vista hills give rise to hills of considerable height above the valley level. The location of the outlying folds that may exist is therefore more difficult to determine in the area here studied than in the areas to the north and south, which, with their better exposures, may be studied as a guide to the type of structure that is present within the valley and that may be expected to occur within this area.

KNOWN ANTICLINES WITHIN THE VALLEY AREA.

Only three main anticlines—the Lost Hills, Antelope Hills, and Belridge—are known to be present within the valley area of northwestern Kern County, and in all three of these anticlines oil has been produced. The drill records are the chief evidence of the existence of two of them.

The presence of the Lost Hills anticline is strongly suggested by the topography, and besides it has been proved to exist by the drill records. The hills consist of a ridge that has a maximum height of 150 feet and is about 8 miles long from northwest to southeast and about a mide wide. The western slope is very gentle, but the eastern slope is steeper and has been dissected to the depth of a hundred feet by the headward erosion of a number of large gullies. The Lost Hills have been so named because, though easily seen from the east, they appear to be lost to one on the west, where the slight eastward rise is hardly apparent to the eye. That the hills are determined by structure is indicated by their straight trend and long and narrow form, as well as by the presence toward their north end of several low parallel ridges that can hardly be other than the topographic expression of underlying beds that are more resistant to erosion than the rest. Outcrops are rather scarce, and in many places the character and attitude of the beds that crop out is difficult of recognition because of the presence of superficial deposits of gypsum. Several of the outcrops appear to belong to the McKittrick formation, which, however, is difficult to distinguish from Quaternary gravels. A few dips may be seen in the supposed McKittrick formation in the hills, but the measurements of all of them are open to some question. Such dips as were seen are less than 10° E., and no dips on the western flank of the anticline were found. This evidence of itself might only indicate a resistant zone in an eastward-dipping monocline. The most convincing surface evidence of the anticlinal character of the hills is their trend, which is directly in line with the Kettleman Hills anticline distant about 5 miles from their northwest extremity.

The logs of wells in the Lost Hills field show a well-marked anticlinal structure, with dips of 15° on the flanks of the fold, in beds of the McKittrick formation. This dip contrasts with the lower dips of the surface gravels and with the lower slope of the flanks of the hills where they have not been affected by recent erosion. Although several wells have passed into the underlying Maricopa shale, the evidence is not sufficient to determine the structure in the shale, though there may be an anticline in the shale that has considerably steeper dips than those in the overlying McKittrick formation. The Maricopa shale lies beneath the McKittrick at a depth beneath the surface of only 1,000 feet or less, as contrasted with the Kettleman Hills, in which, according to Arnold, there is a thickness of over 5,000 feet of the Jacalitos and the Etchegoin formations between the Paso Robles and the Maricopa shale. This shows that there must be a pronounced rise in the structure of the Maricopa shale between the south end of the Kettleman Hills and the north end of the Lost Hills.

The surface evidence for the existence of an anticline in the Antelope Hills is rather less convincing than is that for the Lost Hills. The Antelope Hills consist of a rather low rise trending from a locality southeast of Shale Point southeastward as far as the North Belridge or Manel Minor oil field. The hills rise to a maximum of about 50 or 75 feet above the valley and at several points are completely traversed by arroyos that lead eastward from the mouths of canyons along the edge of the Diablo Range. The top of the hills is rather flat and does not as strongly suggest a low dome as does that of the Lost Hills. Northwest of Antelope Hills there is an anticline that is traceable southeastward as far as Shale Point, and presumably this fold continues southeastward beneath the Antelope Hills.

The logs of wells drilled in the North Belridge field have not been studied sufficiently by the writer to determine whether they prove the existence of an anticline. However, the anticlinal theory of the accumulation of oil is so well established as regards the California fields that the presence of oil in this area is of itself pretty fair evidence of the existence of an anticline. The well logs indicate that the structure in the McKittrick formation is low, and that the dips are less than 10°. The wells penetrate a considerable distance into the Maricopa shale, which is reached at a depth of about 700 feet, but its dip and structure are not known.

The Belridge oil field is on an anticline, of which, however, there is no surface evidence such as outcropping beds or surface elevation. The field was located by drilling near a small oil seepage. The following data on structure in this field, as determined from well logs, may be quoted from the State mining bureau:[14]

> The work done in that field shows that the shallow oil lies above the brown shale in a number of sands which are separated by blue shales. It also shows that these sands and shales lie unconformably on the brown shale, and that the contact surface is roughly anticlinal in form. This should not be construed to mean that we have exact knowledge as to the dip and strike of the individual beds of the brown shale, for we have not. The overlying sands and blue shales form a broad, flat anticline over this irregular ridge of brown shale, but only the upper sands are continuous.

The brown shale spoken of here is the Maricopa shale, and the overlying sands belong to the McKittrick formation. The much smaller thickness of the McKittrick formation in this field than that shown in a section from the hills in sec. 27, T. 28 S., R. 20 E., southwestward to the base of the McKittrick, indicates that there is a pronounced anticline beneath the oil field. In all probability the dip of the Maricopa shale in this field is considerably steeper than the dip of the McKittrick. The areal relations suggest that the anticline on which this field is situated is a southeastward continuation of the McDonald anticline.

The North McKittrick Front field may also lie on an anticline which, like the Belridge anticline, has no surface expression, though the well logs available at present do not give sufficient evidence on which to base any conclusions as to the structure. In fact, much of the trouble caused by water in this field resulted from the lack of similarity of the recorded logs of the wells, so that the structural conditions could not be determined, and thus any satisfactory solution of the trouble, such as shutting the water off at a uniform

[14] McLaughlin, R. P., California State Min. Bur. Second Ann. Rept., p. 239, 1918.

stratigraphic position, could not be accomplished. This anticline may be a northwestward continuation of the Elk Hills anticline of the McKittrick field.

PETROLEUM RESOURCES.

DEVELOPED FIELDS.

HISTORICAL SKETCH.

The first productive field to be developed in this region was the Lost Hills field, the first well in which was drilled in 1910. Thereafter the Belridge, Manel Minor (now called the North Belridge),

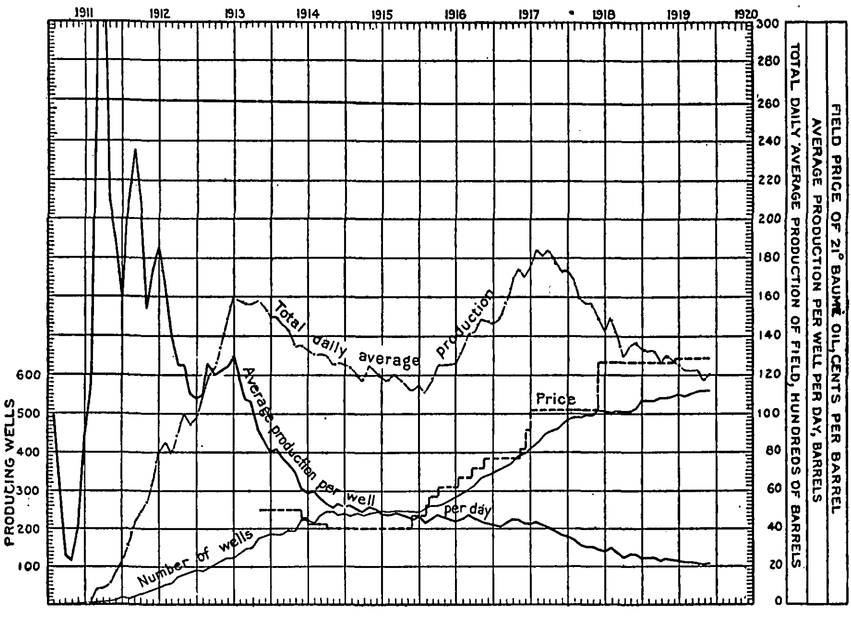


FIGURE 2.—Diagram showing the production of the Lost Hills, Belridge, Manel Minor (North Belridge), and North McKittrick Front fields, 1910–1919.

and the North McKittrick Front fields were successively developed. The number of producing wells and the combined production of the first three of these fields are shown on the accompanying chart (fig. 2), together with the price of oil. The figures used are those of the Standard Oil Co. of California. The graph of the total production shows four separate trends, representing four phases in the history of these fields. The first period extends from the middle of 1911 to the middle of 1913, during which the daily production increased from a few hundred barrels to about 16,000 barrels a day. This phase represents the initial rapid development of a new field (the Lost Hills) and was accompanied by an increase to a total of about 125 producing wells. The fall in the average daily production of each well from a maximum of 400 barrels a day during the initial stages of the field to 125 barrels a day, though rapid, was not sufficient to offset the effect of the rapid increase in the number of wells. The second period extends from the middle of 1913 to the end of 1915, during which there was a gradual decline in the total daily production of the fields to 11,500 barrels a day. During the first part of this period the decline resulted from the continued rapid falling off of the average production of the wells, which dropped to 60 barrels a day and which was not offset by the continuation of an active drilling campaign. During the later half of this period the falling off in average production was very much less, because the period of flush production had passed, but the low price of oil caused a practical stagnation in drilling, and the result was a decline in total production. The third period lasted from the beginning of 1916 till September, 1917, during which there was a gradual increase in total production, brought about by the high price of oil, which stimulated drilling, together with the addition of the Belridge and North Belridge areas as productive fields. The fourth period extends from September, 1917, to the present time, during which there has been a decline in production despite the stimulation of high prices. In this period the field enters upon its old age, during which an inevitable decline takes place, and the possible effect on production of high prices is small.

In addition to the fields mentioned, there are two smaller fields—the Devils Den and Temblor Ranch fields—within the area in which the Tertiary formations outcrop. These fields have had some production, though it is very small in comparison to that of the other fields. The Devils Den field contains four or five wells only a couple of hundred feet in depth, which get a barrel or two of oil a day from shaly beds below the hard Vaqueros sandstone reef bed. The Temblor Ranch field draws its oil from approximately the same horizon and is also very shallow territory. However, some of the wells in this field are reported to have produced for a short time in 1911, during the most productive stage of the field, as much as 200 barrels a day of oil that had a specific gravity of about 15° Baumé. Water in considerable volume soon made its appearance in the wells and the production dropped to a maximum of 10 barrels a day in one or two of the best wells. This area was one of the first areas in the State prospected for oil. Wells were drilled near the seeps in this area during the early sixties, when the oil industry was just getting its start in the United States. Even before that time it is reported that the old settlers used the tarry oil from the seeps to grease their wagons.

GEOLOGY.

Devils Den field.—The small amount of oil produced in the Devils Den field comes from a few shallow wells, less than 200 feet deep, in sec. 25, T. 25 S., R. 18 E. The oil comes from a sandy bed in the shale, mapped as Oligocene (?) by Arnold and Johnson, which lies just below the rather prominent Vaqueros reef bed. Possibly where this bed lies at a greater depth it will be more productive.

Lost Hills field.—The productive territory of the Lost Hills field is now completely outlined, and sufficient development has been done to determine the structure with considerable accuracy. Most of the oil comes from the basal beds of the McKittrick formation, directly overlying the Maricopa shale, which is supposed to have been the original source of the oil. The structure is anticlinal and the dips are 10° to 15° on the flanks of the fold in the McKittrick formation. There is considerable irregularity in the McKittrick, sandy beds, shale, and clay being interbedded in lenticular bodies which can not be correlated with certainty in different parts of the field. The oil comes from several sands which extend through a stratigraphic thickness of a couple of hundred feet, stray oil sands being found at different horizons within this zone, though two main sands yield most of the oil. There is a general plunge of the beds to the south and a further increase in depth southeastward, because at the southern end of the field the oil sands lie at a lower horizon than at the northern end of the field. Toward the flanks of the anticline the sands seem to diverge from the underlying shale, so that a bed a certain distance above the shale on the axis of the fold will be farther above the shale on the flanks of the fold. The wells range in depth from 300 feet at the north end of the field to 1,600 feet at the south end, where the oil is replaced by edge water, which likewise limits the field on the flanks of the anticline.

The quality of the oil differs according to the distance above the shale, the lightest oil coming from the beds close to the shale, near the axis of the anticline, and the heavier oil from upper beds and those farther from the axis. In the southern part of the field the oil ranges from 30° to 38° Baumé, whereas farther north oil from 15° to 30° is obtained from the upper sand.

North Belridge field.—The oil in the North Belridge field comes from two horizons both in the Maricopa shale and about 1,500 feet apart. The McKittrick is only about 700 feet thick here, and below it is the Maricopa shale. The upper oil zone is reached at a depth of about 2,500 feet and the lower at about 4,000 feet. Above the lower zone lies a water sand, which has been rather troublesome in some of the wells. The well logs available are insufficient to establish the anticlinal character of the field. The wells that reach the lower zone are the most productive, and their maximum initial capacity is 1,000 barrels, whereas the capacity of those in the upper zone is only about 50 to 100 barrels a day.

Belridge field.—In the Belridge field, as in the North Belridge field, the productive sands lie at two horizons a considerable distance apart. Most of the oil is derived from sands in the McKittrick formation a short distance above the Maricopa shale. These wells are from 600 to 1,000 feet deep. The sands are lenticular and correlations between wells are rather difficult, so that the details of structure are imperfectly known. It appears that there is a low anticline in the McKittrick formation. Several water sands are apparently interbedded with the oil sands and thus careful mechanical work in drilling the wells is necessary. The lower oil zone, which lies in the Maricopa shale, has been reached in a few wells at a depth of about 3,000 feet. The oil, like that produced elsewhere in the shale series, is light and the initial production is good, but the wells fall off rapidly and water infiltration is troublesome.

Temblor Ranch field.—In the Temblor Ranch field the oil occurs on the south flank of a small anticline at about the same horizon as in the Devils Den field. This horizon is in the lower 2,000 feet of the series, as shown in section 1, Plate I. The limits of the field are defined for the known sand, but lower productive sands may be present. The oil is viscous and its gravity is about 15° Baumé. Only the crest of the fold is productive, and the dips are rather steep, possibly 25° to 30° along the limits of the field.

PROSPECTIVE AREAS.

AREA OCCUPIED BY EXPOSED TERTIARY FORMATIONS.

New fields may be discovered either in the area in which the Tertiary formations of the Diablo Range outcrop or in the area covered by the alluvium of the San Joaquin Valley. The chance of finding new fields appears to be much better in the San Joaquin Valley, even though in the other area the structure is much more perfectly known. In fact, because the knowledge of the structure of the hills is fairly complete, it may be said, with fair assurance of correctness, that there is little chance that fields will be found within that area. The chief reason for the lack of favorable areas to prospect in the hills is that there are no large areas of Maricopa shale properly folded and overlain by sufficient cover to retain any oil which may have been formed in it. The only area of seeming promise in the hills is the region of Temblor Valley, where the eastward-trending anticlines in the Maricopa shale may contain oil at the same horizon as the oil found in the Temblor Ranch field. At best any such fields would probably be of small extent and small yield. Another possible area is the southeast side of Temblor Valley, where the Maricopa shale is closely folded but where some of the folds might be productive like those in the old McKittrick field, where steeply folded beds on a sharp, overturned anticline yield the oil.

AREA INCLUDED IN SAN JOAQUIN VALLEY.

General features.—The oil pools thus far discovered within the area of the San Joaquin Valley are determined by anticlinal structure, and the existence of other pools is probably dependent on the existence of anticlines other than those now productive. The problem presented is whether there exist any other anticlines which are favorable for testing, and if so to determine if possible their locations. There are no outcrops of Tertiary beds, nor is there other surface evidence to indicate the presence of anticlines other than those now productive, though there is some evidence of the extension of the known folds beyond the areas which have been thoroughly tested. The following discussion therefore relates largely to the possibility of finding new productive folds by drilling more or less at random within the alluvium-covered area of the valley. The only guide to such drilling would be an assumed trend of folds parallel to the other folds of the region and a distance between the folds similar to that between the folds in the areas where they are exposed at the surface or otherwise proved to exist, and an assumed continuation of the known folds beyond the areas where their presence is already proved.

The first point to be considered is the likelihood of the existence of buried folds. It is therefore pertinent to inquire what are the surface features by which the known folds are marked, and what, if any of them, may be expected to mark any other folds that may exist. The surface evidence of the presence of the known folds, which incidentally are all productive of oil, are topographic rise, outcrops of Tertiary formations within an otherwise alluvium-covered area, and the presence of oil seeps. In the following paragraphs it will be demonstrated that all anticlines may not be marked by hills. Likewise, the outcrops of Tertiary formations are not necessarily present, as they only indicate the presence of a former range of hills composed of Tertiary rocks which has been completely buried as a topographic feature but in which the covering over the crest is so shallow that the underlying Tertiary beds outcrop in a few isolated places. The presence of oil seeps is also obviously dependent on the thickness of the beds overlying the oil-bearing horizon and their permeability to the upward-migrating oil, so that if the cover is thick or especially impervious there would be no seeps, even though there was a large amount of oil in the underlying rocks.

In the writer's view, hills are not necessarily present in areas that have anticlinal structure. The correspondence between topographic forms and the forms of the Tertiary anticlines is not as close as has often been stated. Both the Lost Hills and the Antelope Hills anticlines are marked by hills as topographic features, but on the other hand the topographic features in the Belridge and North Belridge fields show little or no indication of the folds. The Lost Hills and the Antelope Hills are remnants of much more prominent hills which were formed during the post-McKittrick period of folding. After their uplift they were eroded to low domelike forms and a small thickness of gravels was deposited over their crests. More recently a slight climatic change has resulted in the cutting of numerous small gullies on the flanks of the otherwise even domes. Except for the recent modification in form they represent mature to old-age topography of an arid cycle. These hills conform to the Tertiary anticlines in location, but their slopes are less steep than the dips in the underlying McKittrick formation. Also the location of the hills may be somewhat shifted from the area directly over the anticlinal axes, because of unequal erosion, as apparently has happened in the Lost Hills.

This conception of the origin of the present topographic features and of their relation to underlying structure is significant and differs markedly from theories previously advanced and widely accepted. Thus Arnold and Johnson apparently hold that the even, domelike form commonly presented was produced by an uplift, which has been followed by no great amount of erosion. They say:

> Seen from a distance, Elk Hills, if the very youthful but very numerous drainage lines be eliminated, must present much the same appearance that it did when formed.[15]

Presumably the term "when formed" refers to the post-McKittrick period of folding, as there is no mention of any later folding believed to have taken place. Also, it is implied, though not explicitly stated, that they not only "present much the same appearance as when formed," but that they are in fact the original hills, practically unaltered by erosion, which were formed by the uplift mentioned. With regard to the Lost Hills they state:[16]

> While the evidence is not absolutely conclusive, the Lost Hills range, which rises about 200 feet above the surrounding plain, is believed to be an anticlinal fold of such recency that its original form, except for the erosional scorings upon the surface, has not been lost.

The writer's view is that the dome of the Elk Hills, like that of the Lost Hills, is an old-age feature of erosion in an arid climate, and that the hills have been subjected to a very large amount of erosion in

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[15] U. S. Geol. Survey Bull. 406, p. 76, 1910.
[16] Idem, p. 76.

post-McKittrick time. According to the theory of Arnold and Johnson, there would seem to be very little chance that any post-McKittrick folds could exist without an expression in the topography, and consequently prospecting in areas unmarked by hills would have very little likelihood of success. On the other hand, if we assume that there has been a great deal of erosion since the hills were formed, it may well be that other structural hills have been eroded to such an extent that they have been overridden by the rising level of Quaternary gravel and are consequently no longer represented by any topographic feature whatever.

That the writer's view of the origin of the hills is correct seems to be proved by the lack of correspondence between the geologic structure and topographic form of several ranges of hills. The most striking illustration of this divergence, perhaps, is Kettleman Hills, in the Coalinga area to the north. Kettleman Hills were presumably formed at the same time as Elk Hills and Lost Hills. Kettleman Hills are a low domelike range of hills, slightly modified by recent erosion, essentially similar in form to Elk Hills. However, the geologic structure leaves no possible doubt that there has been a great deal of erosion since their uplift, as the Paso Robles and upper Miocene formations, if restored over the crest of the anticline of the hills, would produce a range of mountains 6,000 or 7,000 feet high, though the hills are at present only as many hundred feet above the surrounding plains. Likewise all along the edge of the Temblor Range, between McKittrick and Sunset, the McKittrick has been affected by a great deal of erosion since the post-McKittrick uplift. It seems hardly likely that there would be any such discrepancy in the amount of erosion in post-McKittrick time as would be necessary if the Elk Hills and Lost Hills are only very slightly modified in form since their original uplift. Though the Elk Hills conform very closely in form to the underlying structure, the dips on the flanks of the hills are rather greater than the slope of the surface. Such agreement in form as there is between topography and structure is probably due to the fact that the beds forming the hills are of fairly uniform hardness throughout, so that in the course of erosion there would be very little tendency for hard beds to form prominent ridges and cause the shape of the hills to depart from that developed by the original uplift. Also, it happens that the structure of the hills would present nearly the same topographic form as that which they would tend to take in the normal course of arid-climate erosion. In the Lost Hills, too, the structure of the McKittrick formation does not parallel the slope of the surface dome but is much steeper, as is proved by the well logs, a line of evidence which was not available at the time that Arnold and Johnson wrote.

If the form of the different ranges of hills is not that developed by the original post-McKittrick uplift, it may still be urged that they were formed by a later uplift, possibly in late Quaternary time, since which they have been only slightly modified by erosion. This hypothesis, too, seems unlikely to the writer, though it is less easily disproved than the one just presented. If such a later uplift had occurred, there would probably be some beds that were deposited in post-McKittrick time but prior to the supposed uplift and that had been tilted by it. Yet no such beds are present. All the Quaternary gravels show only such dips as they probably had when they were deposited. Further, the form of the Lost Hills is not one that would probably have been developed by uplift alone. They form a topographic terrace that has a comparatively steep slope on the east and a very low gravel-covered slope on the west. This form is easily accounted for, and would be expected if a low dome had been overridden by gravel deposits from the west; but a structural terrace of this type would be a rather peculiar form for an uplift to take. Likewise, the low parallel ridges which occur along the length of the hills could hardly have been formed by an uplift unmodified by erosion, though they are easily accounted for as the result of the action of erosion on tilted beds of unequal hardness.

As shown by the preceding discussion, if other folds were formed within the valley area they may have been completely hidden, as far as surface evidence goes, at the present time. But is there any reason to believe that any such folds were actually formed? Are there any buried folds between those now known, or are there others farther out in the valley than those now known? There is no direct evidence bearing on this question. The likelihood of such folds depends on whether the folding which took place was sporadic in character or whether it affected all parts of the area over which it took place without leaving any unfolded areas or "holes" in a region in which the rocks elsewhere were folded, and on how far eastward in the valley the folding extended. It would seem that as the folding was a result of stresses which acted over large areas the folding was continuous over those areas but with diminishing intensity from the center of greatest activity, and that in so far as the beds presented fairly uniform resistance in adjacent areas the folds were probably of about the same steepness and about the same distances apart but in general of decreasing intensity toward the valleys, irrespective of whether the folds are exposed to view or are masked by alluvium. Thus there may well be one or more anticlinal folds in the wide alluvium-covered area between the Lost Hills and the edge of the Temblor Range to the west.

The distance to the east that the folding extended is rather harder to approximate. The Lost Hills anticline marks the eastern limit of the known folds, and on the east side of the valley, in the region of the Kern River oil field, where the Tertiary beds are well exposed, there is a more or less regular low monoclinal dip toward the west. However, on the east side of the valley the Tertiary beds are comparatively thin and rest on a rigid granitic basement, which slopes gradually toward the west under the valley.

The presence of this rigid foundation may have prevented the folding of the Tertiary rocks as they have been folded along the western margin of the valley. The eastern limit of folding very likely lies along a line where the granitic rocks reached such a depth that they were below the zone of activity of the forces causing the folding in this interior area. This line can not be determined from the surface, but it is reasonable to postulate that the forces which caused the folding did not die out abruptly. The folding in the Lost Hills is rather marked, and the absence in that region of so large a thickness of upper Miocene beds (representing the Jacalitos formation and the lower part of the Etchegoin formation) indicates that in the past, at least, there was considerable folding and uplift in a part of the valley far out from the edge of the present Coast Ranges. The writer's opinion therefore is that in Tertiary time San Joaquin Valley was not a geosyncline of unfolded Tertiary beds, but that there were anticlines and synclines of considerable magnitude farther out in the valley than the Lost Hills fold. The possible location of such folds as may exist between or beyond the known folds will be discussed in the following description of separate areas within the region studied.

Area between Lost Hills and Temblor Range.—In the alluvium-covered area some 12 miles wide between the Lost Hills and the edge of the Temblor Range one or more folds may be present. Elsewhere the anticlines out in the valley beyond the edge of the mountains are from 4 to 6 miles apart and are progressively closer together the nearer they are to the edge of the mountains.

The folds in this area are probably not farther apart than elsewhere and thus suggest the presence of an anticline about midway between the Lost Hills anticline and the North Belridge (Manel Minor) anticline.

The presence of an anticline in this area is also suggested by the structure of the Tertiary rocks on the two sides of Antelope Valley. The pre-Miocene formations outcrop much farther to the east on the north side of Antelope Valley than on the south side. The Miocene beds which form Wagonwheel Mountain must therefore swing westward around the axis of a plunging anticline or else be faulted down on the southwest side. A fault with downthrow on the southwest side has brought Miocene beds into contact with older rocks near the head of Antelope Valley. This fault probably continues a considerable distance to the east beyond the area where it is exposed, probably well into T. 26 S., R. 18 E., but still farther east it may give way to an anticline, like many of the faults which extend eastward into the zone of less intense folding. There is therefore some reason to suspect the presence of an anticline trending southeastward from a point south of Point of Rocks, possibly passing near the 707-foot bench mark in sec. 20, T. 26 S., R. 19 E. Such an anticline should be favorable for the accumulation of oil.

The stratigraphy and structure of the rocks beneath Antelope Valley west of a line drawn north and south through Point of Rocks is probably similar to that of the hills on either side; and if so, the rocks are too much disturbed and the older formations are too extensive for this area to be favorable for prospecting for oil.

Possible continuation of McDonald anticline.—The McDonald anticline is traceable for a distance of about 15 miles in the hills. At its north end the fold has its origin in the much-faulted area west of Barril Valley. From the north line of T. 27 S. it is traceable southeastward as a well-marked steep fold. Just north of Bitterwater Valley there is a southward plunge of 15° to 20°, which brings the shale over the axis. South of Bitterwater Valley the fold is less closely compressed, and the doming brings up the Tejon along the axis. Where the fold approaches the valley alluvium toward the southeast it plunges 8° to 9° southeastward. Beyond the edge of the valley there is no topographic evidence of its continuation. The other folds that are known to extend out into San Joaquin Valley are marked by low hills, so there is some doubt as to whether this fold extends to the southeast or plunges steeply and merges with the monocline that flanks the range south of this region as far as Gould Hill, as does the Ciervo anticline, north of Coalinga,[17] which is well marked in the higher hills but plunges to the southeast and merges with the monocline along the edge of the valley. It has, however, already been pointed out that there is no surface evidence of the probably continuous anticline between Lost Hills and Kettleman Hills, so the lack of surface evidence does not preclude a continuation of the McDonald anticline. The writer believes that this anticline, which is traceable for a considerable distance within the hills, may not terminate at the edge of the valley, but that more likely it continues for at least several miles beneath the Quaternary valley filling. The position of the Belridge oil field suggests that it lies on a continuation of this anticline.

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[17] Anderson, Robert, and Pack, R. W., Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, Calif.: U. S. Geol. Survey Bull. 603, geologic map, 1915.

Gould Hill to the McKittrick Front.—In Gould Hill there are several small folds in the McKittrick formation that trend N. 60° W., and in the north end of the McKittrick Front similar small folds that trend N. 75° W. Between the two areas lies the alluvium-covered Temblor Valley, along the west side of which the folds in the Vaqueros and Maricopa rocks trend nearly east. The probable extension of these folds must be considered. The folds from the west side of the valley may extend eastward between Gould Hill and the Temblor Front or, as appears more likely, they may swing around toward the southeast parallel to the trend of the folds in the McKittrick formation and possibly connect with the folds in the hills northwest of McKittrick. In sec. 8, T. 29 S., R. 20 E., the Maricopa shale strikes nearly east, although the contact at the base of the McKittrick trends N. 30° W., and in the small area in which the shale crops out in secs. 7 and 18, T. 29 S., R. 21 E., its strike is considerably nearer east than that of the surrounding McKittrick formation. It therefore seems likely that the east-west folding was produced previous to the folding that affected the McKittrick formation, and therefore none of the folds in the McKittrick trend east. The small folds in Gould Hill probably continue southeastward beneath the alluvium and are not affected by the folds mapped on the west side of Temblor Valley.

The folds in the hills of the McKittrick Front and on the east flank of Gould Hill are small and close together. Apparently as the folds approach the edge of the main range they become progressively closer together. This close folding probably does not extend far out from the hills, and any folds farther out than the north McKittrick Front are probably wide apart and regular in structure. The writer thinks that possibly the Belridge anticline continues southeastward parallel to the McKittrick Front and that this area would be more likely to contain a well-developed anticline than the area nearer the hills on the west. Another place which seems rather favorable is in the locality where the Lost Hills and North Belridge anticlines would intersect if projected, for if either of the two folds continues with unaltered direction there would be an anticline at that place.

Region east of the Lost Hills anticline.—Though there is no surface evidence of the presence of any folds east of the Lost Hills, the possible value of any discovery in this area makes it advisable in the writer's opinion to test the region far out in the valley by one or more deep wells. Even if an initial well failed to obtain any oil, if the Quaternary deposits were found to be thin the indications would be favorable and would warrant further prospecting. In view of the spacing of folds elsewhere the writer suggests that a belt 6 to 8 miles east of the Lost Hills anticline would include the area in which another anticline is most likely to be present.

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