GEOLOGIC SUMMARY OF THE CENTRAL VALLEY OF CALIFORNIA, WITH REFERENCE TO DISPOSAL OF LIQUID RADIOACTIVE WASTE

By Charles A. Repenning

UNITED STATES DEPARTMENT OF THE INTERIOR
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Charles A. Repenning

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This report is preliminary and has not
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ABSTRACT

The Central Valley of California lies west of the Sierra Nevada and east of the Pacific Coast Ranges. It is about 450 miles long and has an average width of about 40 miles. The northern part is drained by the Sacramento River and is called the Sacramento Valley. Much of the southern part is drained by the San Joaquin River and the remainder has an interior drainage; the southern part is called the San Joaquin Valley.

As much as 6 miles of sedimentary rocks accumulated in the San Joaquin Valley and as much as 10 miles in the Sacramento Valley. Most deposits in the Sacramento Valley are composed of Cretaceous sandstone and siltstone with little regional variation. The deposits in the San Joaquin Valley, by contrast, are largely Tertiary sandstone, siltstone, and claystone with great regional variation in rock types. The complexity of the facies of the Tertiary rocks has resulted in a large stratigraphic nomenclature, and much of it, because most of the information is from well data, is loosely defined and of informal nature. It is, nevertheless, widely used, and must be used in any regional summary of the stratigraphy.

Cretaceous deposits are largely marine, but the Tertiary rocks contain a high proportion of continental deposits that are increasingly abundant in the younger parts of the stratigraphic section. Many stratigraphic traps of several types are present that might be used to store liquid waste. The potentially useful stratigraphic storage reservoirs are common and the selection of more favorable areas for waste disposal is influenced by areas of favorable geologic structure.
This report has been prepared as a part of the Radioactive Waste Disposal Program of the Division of Reactor Development, Atomic Energy Commission. It is the second of a series of reports covering areas underlain by sedimentary rocks in the United States. The first was a summary of the San Juan Basin, New Mexico, released to open file in September 1959 as TEl 603 (Repenning, 1959).

These reports describe the geology of the area only to the extent necessary for preliminary evaluation of the possibilities for the disposal of liquid radioactive waste by injection through deep wells. Their value will increase with development of extensive commercial production of atomic power and attendant creation of radioactive waste from the processing of spent fuel elements. The disposal of liquid waste in deep reservoirs is only one of several possibilities that must be considered. Many factors must be considered in disposing of radioactive wastes, such as certainty of containment for the duration of hazardous radioactivity, monitoring requirements, regional and local hydrology, engineering problems, and cost. These factors can be more adequately evaluated when a specific disposal site is considered. Although this report is not sufficiently detailed for specific site selection it may be used as a guide to more favorable areas through the generalized picture of the important subsurface geologic conditions. No recommendations for any site, medium, or method for waste storage are made. But areas are pointed out that appear more favorable for waste disposal under certain assumed conditions, chosen to provide a basis for discussion of waste disposal possibilities.
This report is based on existing literature except that unpublished vertebrate fossil records on file at the University of California, Berkeley, have been used in establishing some age relations and correlations. These data are not mentioned in the text, and their effect will be noted only by those who are familiar with the stratigraphy of the area.

The author has accepted or modified published records to the best of his judgment, as otherwise the report would be a maze of conflicting statements. Unless directly quoted, references to published material in the following text do not necessarily reflect the precise meaning of the person cited.

The stratigraphy of the Central Valley of California has many currently irresolvable problems, partly regarding temporal equivalents of rock units but particularly regarding assignment of these rock units to standard time divisions of the Cretaceous and Tertiary. Temporal equivalence of different rock units is important in establishing the areal extent of units of possible significance for either oil exploration or waste disposal. Differences in interpretation of local correlations in the Central Valley of California are few, and most of the correlations shown on figure 3 and discussed in the text are reliable. Question marks indicate that some uncertainty exists. Correlation of rock units within the Central Valley to the standard rock chronology of the world is subject to diverse opinions, which, fortunately, have no bearing whatever on the problems of waste disposal.

In accordance with the custom of discussing the stratigraphy of any area in terms of the standard rock ages of system and series, the author has adopted the most commonly used age assignments of the rock units. In some cases these assignments to series disagree with those of The Geologic
Names Committee of the U. S. Geological Survey, and in some cases the author believes other assignments more reasonable.

Subdivision of series into upper and lower (or upper, middle, and lower) parts will undoubtedly be questioned by some readers. The subdivisions of series shown on figure 3 and used throughout the text are used by the author only for arrangement of the stratigraphic discussion. They are convenient groups of rock units which can be discussed as an entity throughout the Central Valley and have no implied correlation to upper, middle, or lower divisions of the type series in Europe. Thus, the series subdivisions are a purely artificial device for convenient grouping for the purposes of the present report, and the same is true of the series assignments, except that they represent the majority of published opinions.

In order to explain the assigned age of stratigraphic units shown in the age column of figure 3, it was necessary to include the three Pacific Coast faunal "age" scales. One example illustrates this need. In several areas in and adjacent to the Central Valley, the Santa Margarita sandstone contains both continental vertebrate and marine molluscan faunas. The vertebrate material indicates an early Clarendonian provincial mammalian age, and the mollusks indicate a Cierbo or Neroly megafaunal "age." Most workers correlate the Clarendonian with the lower Pliocene of Europe and the Neroly and Cierbo with the upper Miocene of Europe. The assignment of the Santa Margarita either to Miocene or to Pliocene on figure 3 would immediately arouse debate, but the assignment to the Clarendonian, the Delmontian and Mohnian, and the Neroly and Cierbo "stages," zones, or provincial stages is specific and valid. The assignment of the Santa Margarita to the upper Miocene is arbitrary and admits
variation. Its correlation to the three "age scales" of figure 3 is based upon faunal evidence. Similar examples of disagreement of correlation with the standard European series are present throughout the Tertiary and between all three faunal age disciplines. The columns do not concern local stratigraphy but are included as explanation for relations to areas beyond the limits of the Central Valley of California.

The geology in many parts of the Central Valley is poorly known because the older rocks are masked by younger Pleistocene and Recent sediments. Only in scattered areas around the margins of the valley, mainly on the west side, do the older rocks crop out. Therefore, knowledge of the geology in the covered parts of the basin is dependent upon the amount of subsurface data available. These data tend to be concentrated in local areas of economic interest, and many large areas within the valley are still undrilled. Only published subsurface data have been used in preparing this report. Unpublished well data in many areas are available only after negotiation with the operating companies.

The stratigraphic nomenclature of the Central Valley shown on figure 3 reflects this lack of available information. Many informal rock names are in common use. These units cannot be defined more precisely until correlations between areas can be established by detailed work.

The Central Valley of California, also called the Great Valley of California, is nearly flat west of the Sierra Nevada and east of the Coast Ranges (fig. 1). It is about 450 miles long, extending from the Tehachapi Mountains on the south to the Klamath Mountains on the north. The valley has an average width of about 40 miles and a maximum width of about 75 miles. Most of the valley is near sea level and all of it is below 1,000 feet in elevation.
Figure 1. Index map showing generalized geology of California.
The northern part of the Central Valley is called the Sacramento Valley and the southern part is called the San Joaquin Valley. Rivers of the same name drain most of the area, entering the Pacific Ocean near San Francisco. The southern half of the San Joaquin Valley has interior drainage.

**STRATIGRAPHY**

The Central Valley is a northwest-trending structural trough that has been filled with a thick sequence of sedimentary rocks ranging in age from Jurassic to Recent. In general, the rocks of Jurassic and Cretaceous age are more widespread in the Sacramento Valley and the Tertiary rocks more widespread in the San Joaquin Valley. The deepest part of the trough is along the western edge of the valley, where as much as 6 miles of sedimentary rocks have accumulated in the San Joaquin Valley and as much as 10 miles have accumulated in the Sacramento Valley (fig. 2).

The thick sedimentary sequence rests on a basement floor composed of metamorphic and granitic rocks. These basement rocks crop out in the hills surrounding the Central Valley and have been reached by wells in many areas. Eastward from the deep part of the basin, the basement floor rises gently and is apparently continuous with the surface cut on the metamorphic and granitic rocks of the westward-tilted Sierra Nevada block. The western side of the Central Valley is probably underlain by basement rocks similar to those forming the core of the California Coast Ranges. These rocks include the "Franciscan" formation, consisting of a heterogeneous mixture of graywacke, shale, basalt, chert, and serpentine, all of which locally have been metamorphosed to glaucophane schist, and granitic rocks that occur in large isolated fault blocks.
The granitic rocks around the Central Valley are Mesozoic (pre-Late Cretaceous) in age, and the "Franciscan" is in part Cretaceous and in part Jurassic. One of the unsolved problems in California is the correlation between the "Franciscan" of the Coast Ranges and its unmetamorphosed age equivalents in the Sacramento Valley (Irwin, 1957). "Basement complex" is the term generally used for these older rocks in the Central Valley, and no attempt will be made to describe or discuss them further.

Cretaceous and Tertiary rocks of marine and continental origin attain a maximum thickness of about 10 miles (fig. 2) in the deepest part of the Central Valley. These rocks are composed almost entirely of clastic material derived from surrounding upland areas. Sandstone, siltstone, and claystone are the dominant lithologic types, and significant amounts of carbonate rocks are completely absent.

The Cretaceous section is characterized by lithologic continuity over large areas. Thick lithologic units have been traced throughout much of the west side of the Sacramento Valley (Kirby, 1943, p. 303-304), and some of these units have been correlated with formations of similar lithology along the west side of the San Joaquin Valley, although south of Mount Diablo Lower and some Upper Cretaceous units are absent. Cretaceous deposits are apparently absent in the southern part of the San Joaquin Valley where the Tertiary rocks attain their maximum thickness.

In contrast to the regional lithologic similarity of the Cretaceous rocks, the Tertiary section is highly variable, particularly in its younger part, and many rock units are correlated with considerable uncertainty over distances of only a few miles.

The Cretaceous sediments were probably derived largely from the rocks that at one time covered the granitic mass of the Sierra Nevada, but
localized source areas in the Coast Ranges to the west may also have contributed. Tertiary rocks, by contrast, are more arkosic and presumably were derived from the granitic batholith of the Sierra Nevada. In some areas, marine Cretaceous rocks may have covered large areas between the present Central Valley and the Pacific Ocean. The Tertiary Central Valley was structurally more distinct than the Cretaceous basin and probably had only a restricted connection with the Pacific Ocean.

**Pre-Cretaceous rocks**

The oldest known sedimentary unit in the Central Valley is the Knoxville formation of Late Jurassic age. It crops out locally along the west side of the Sacramento Valley from the north side of Mount Diablo northward to Paskenta. The eastern limit of the Knoxville is unknown. The Knoxville consists mainly of well-indurated marine shale and siltstone as much as 10,000 feet thick. Locally present are relatively thick units of impermeable argillaceous sandstone and conglomerate, and minor lenses and thin beds of limestone.

The base of the formation is not exposed in the Sacramento Valley. In most areas the contact with the overlying Cretaceous rocks is gradational, and similar lithologies above and below the contact represent continuous deposition from Jurassic into Cretaceous time. Locally an unconformity is reported between the two units, and in other areas a conglomerate is arbitrarily selected as the base of the Cretaceous. Marine fossils indicative of a Late Jurassic age are locally present in the Knoxville.
Cretaceous rocks

Lower Cretaceous rocks are present only in the Sacramento Valley but Upper Cretaceous rocks are found throughout the Central Valley. The Cretaceous rocks have a maximum thickness of about 25,000 feet in Sacramento Valley and are about 20,000 feet thick near Coalinga in the San Joaquin Valley (fig. 4).

Lithologic similarity throughout the thick Cretaceous section has made division into formational units difficult, and faunal changes are generally more distinctive than changes in rock type. Rocks of Early Cretaceous age are often assigned to the Shasta series and rocks of Late Cretaceous age to the Chico series. Local formation names are frequently used within this series classification.

Shasta series.--The Shasta series, present only on the west side of the Sacramento Valley as far south as Mount Diablo, consists of about 10,000 feet of mudstone and siltstone with some interbedded conglomerate and argillaceous sandstone. Nodules, lenses, and thin beds of limestone are present in minor amounts. The Shasta series has so little lithologic variation that it has not been divided into formations in most areas. Its fauna has been divided into the older Paskenta stage and the younger Horsetown stage. Murphy (1956) has named two lithologic units in the northern Sacramento Valley. These are the Rector formation, consisting of about 400 feet of sandstone, conglomerate, and mudstone that rests on an igneous basement; and the overlying Ono formation, consisting of 4,200 feet of mainly mudstone and siltstone (fig. 3, column 2). The Ono contains two conglomeratic and argillaceous sandstone tongues. Murphy correlates most of his section with the Horsetown stage of the southern Sacramento Valley; a considerable part of the older
FIGURE 4. Distribution and thickness of Cretaceous sediments at the beginning of Tertiary time in Central Valley of California.
Paskenta stage is absent, as is the Knoxville formation. No one has
applied Murphy’s formalional names farther south, and most of the Shasta
series of the Central Valley remains undivided.

Chico series.--The Chico series is much more widespread than the
older sedimentary rocks and is present throughout the Sacramento Valley
and the northern San Joaquin Valley. The contact between the Shasta
series and the Chico series of Late Cretaceous age appears to be completely
gradational and is based mainly on changes in the fauna. Attempts are
usually made to place the contact at a lithologic change near the faunal
boundary. In gross lithology the Chico series is similar to the Shasta
and Knoxville but contains more sandstone and a greater variation of
lithologic types. The average thickness of the Chico is about 15,000 feet
in the western part of the Sacramento Valley, and in general it thins to
the east and northeast. This thinning represents both a reduction in
thickness of correlative stratigraphic units and the eastward onlap onto
basement rock.

The lithologic variation of the Chico series is illustrated by the
number of formations and members that have been recognized in the Central
Valley. These units are generally interbedded sandstone and shale and
have been variously named, or numbered, in different areas. Kirby (1943)
recognized six such units of the Chico in the western part of the
Sacramento Valley. Others have included a seventh, a thick shale unit
underlying Kirby’s lowest formation, not on the basis of lithologic unity
but because it contains Late Cretaceous fossils (fig. 3, column 1).

The Chico series in Kirby’s area consists of about 50 percent sand-
stone and 50 percent siltstone and claystone. Three of his formations
(the Guinda, Sites, and Venado) are sandstone units 1,000 to 4,000 feet
thick. These sandstone units are largely fine to medium grained and quite argillaceous. They are interbedded with minor amounts of shale, and conglomeratic beds are locally common.

Eastward from Kirby's sections the Chico series thins and becomes increasingly sandy. In the Marysville Buttes area (fig. 3, column 3) the exposed section is about 2,750 feet thick (Kirby, 1943, p. 301) and consists of about 35 percent shale and 65 percent sandstone that varies from fine grained and argillaceous to very coarse grained. Subsurface information north of Marysville Buttes indicates that the total Upper Cretaceous section is more than 4,500 feet thick. The unexposed part of this section is predominantly shale, and the uppermost 700 feet, including the fine-grained micaceous and very argillaceous "Kione sand," is of uncertain age and may be Paleocene rather than Cretaceous. These younger units are not present in the western part of the Sacramento Valley.

In the northern part of the Sacramento Valley, east of Redding (fig. 3, column 2), Popenoe (1943) has divided the 4,000-foot Chico section into six numbered units, of which three are clean, fine- to coarse-grained, conglomeratic sandstone. These units range from 200 to 1,000 feet in thickness and make up about 45 percent of exposed section. Popenoe's units seem to be correlative with the middle part of the Chico on the west side of the Sacramento Valley. In general the sandstone units of the Chico in eastern and northern Sacramento Valley contain less argillaceous material and are coarser grained than those along the western side of the valley.

Nearly continuous outcrops of the Chico are found from Mount Diablo southward to Coalinga. Here it is subdivided into two units, the Panoche
formation and the Moreno formation, part of which is of Paleocene age. Locally both the Panoche and the Moreno are divisible into members. In the Mount Diablo area Taff (1935) recognized a third unit beneath the Panoche and overlying the Shasta series (fig. 3, column 6). He referred this unit to the Chico formation, a usage in conflict with the term Chico series. Taff abandoned the Chico as a series name and referred the three formations, Chico, Panoche, and Moreno, to the "Upper Cretaceous series." The Chico series is about 19,000 feet thick in the Mount Diablo area but thins rapidly southward to about 11,000 feet in the Coalinga area (fig. 3, column 10). This thinning may be due largely to the loss of Taff's Chico formation, which is about 7,000 feet thick in the Mount Diablo area.

Taff's Chico formation (1935, p. 1088) has a basal member composed primarily of sandstone and conglomerate that is nearly 1,000 feet thick. This member is overlain by about 1,000 feet of limy and cherty shale. The remaining 5,000 feet are composed of interbedded thin sandstone and shale units. Similar interbedded sandstone and shale, with some conglomerate, continues throughout the overlying 5,000 feet of the Panoche formation. However, southward from Mount Diablo the sand content of the Panoche increases and two prominent sandstone units become recognizable. In the Coalinga area, these have been named the Brown Mountain sand member, at the top of the Panoche, and the Joaquin Ridge sandstone member, separated from the Brown Mountain member by a thick shale member (fig. 3, columns 10, 11). These sandstone members are fine to medium grained and composed of angular to subangular grains of quartz and feldspar. They are relatively free of argillaceous material. In places they are somewhat conglomeratic and much of the sandstone is concretionary. The Joaquin Ridge sandstone member is as much as 4,400 feet thick, and the Brown
Mountain sand member is about 350 feet thick. Near Coalinga the Panoche rests unconformably on Franciscan basement rocks and is in part older than the Panoche of the Mount Diablo area.

The contact between the Panoche formation and the overlying Moreno formation appears to be gradational over most of the western side of the San Joaquin Valley, although Taff mentions the possibility of an unconformity separating the two formations in the Mount Diablo area. The Moreno formation has an average thickness of about 2,000 feet, although Taff (1935, p. 1089) estimates a thickness of 7,000 feet in the Mount Diablo area. The uppermost 1,000 feet is Paleocene in age (Payne, 1951, p. 11). The Moreno is composed of brown, reddish-brown, and gray shale, with some massive sandstone beds in the more northern outcrop areas. Some parts are siliceous and other parts are calcareous; platy diatomaceous shale units as much as 200 feet thick are locally present.

The uppermost part of the Panoche and all of the Moreno are younger than the Chico series in the western, northern, and northeastern parts of the Sacramento Valley. They seem to be approximately correlative with the outcrop section of the Chico at Marysville Buttes.

**Tertiary rocks**

The greatest accumulation of Tertiary rocks is near the southern end of the San Joaquin Valley, where more than 6 miles of sediments have been deposited. Tertiary depositional history is more complex than that of the Cretaceous because of more tectonic activity. Rapid lateral changes in thickness and lithology of the Tertiary rocks have resulted in a large number of formational units, both formal and informal (fig. 3), and complicate any attempt at regional synthesis.
Paleocene rocks.--Rocks of Paleocene age are present in the northern part of the San Joaquin Valley and probably extended into the southern Sacramento Valley. (See p. 13, discussion of "Kione sand"). In most areas, deposition was continuous from Cretaceous into Paleocene time and from Paleocene into early Eocene. Therefore, the time boundaries do not correspond with the formational subdivisions, and it has become customary to discuss rocks of Paleocene and Eocene age, separating rocks of Eocene age from rocks of Late Cretaceous and Paleocene age, which are grouped together as of Paleocene age.

A high area of Cretaceous rocks, known as the Stockton arch (figs. 2 and 5), separates Paleocene, Eocene, and perhaps Oligocene rocks of the southern Sacramento Valley from similar rocks in the San Joaquin Valley. Available information suggests that the Stockton arch is related to the uplift south of Mount Diablo (fig. 5) which became active during Late Cretaceous time. It seems probable, therefore, that during the early Tertiary the southern Sacramento Valley was a separate basin, not connected to the San Joaquin basin but to the Pacific Ocean by a route north of Mount Diablo through the area now occupied by San Pablo Bay and the type Martinez formation. No Paleocene rocks seem to be present south of the Bakersfield arch in the southern San Joaquin Valley (fig. 2).

The type section of the Martinez formation, exposed at the town of Martinez about 5 miles upstream from the head of San Pablo Bay, consists of about 2,000 feet of dark silty claystone with thin, hard, glauconitic sandstone and some conglomerate. The type Martinez, however, contains rocks younger than those ordinarily considered to be of "Martinez" age (fig. 3, column 7). Southeast of the type section, toward Mount Diablo, the Martinez thins to 700 feet of calcareous shale and brown to green
FIGURE 5. Distribution and thickness of Paleocene and lower Eocene sediments at the beginning of late Eocene time in Central Valley of California.
sandstone. The formation pinches out a short distance south of Mount Diablo. It is present in the subsurface to the east and northeast and may grade laterally in this direction into sandy facies such as are exposed beneath the so-called Megamos formation at Marysville Buttes. From the Mount Diablo area south to Pacheco Pass no "Martinez" beds are present; however, south of Pacheco Pass beds of seemingly similar age but of different lithology are present. These beds were assigned to the Laguna Seca formation by Payne (1951) and are primarily a silty, micaceous, fine-grained sandstone (fig. 3, column 8). Farther southward, they seem to grade into the Cerros shale member of the Lodo formation (fig. 3, column 9).

Eastward from the western side of the San Joaquin Valley the Martinez-equivalent rocks are present beneath much of the central part of the valley. However, in the eastern half of the valley they are truncated by one of the most significant unconformities of the area. This unconformity is overlain by the upper Eocene Domengine sandstone or by younger rocks which overlap the Domengine. These units above the unconformity may be equivalent to part of the continental sandstone beds called the Walker formation, although in some areas the Walker may contain beds as young as early Miocene.

Younger Paleocene rocks of the San Joaquin Valley contain more fine-grained to conglomeratic sandstone and are relatively free of significant amounts of argillaceous matrix and probably are quite permeable. In addition to being interbedded with shale units, the sandstone units themselves contain some relatively thin shale beds. They are included in the lower part of the Megamos formation (under several names or letters) and possibly in the lower part of the Cantua sandstone member of the Lodo formation. The Cantua member, however, is generally considered to be part of the lower Eocene section.
Eocene rocks.--Eocene rocks are widespread in the Central Valley and are separated into lower and upper parts by a regional unconformity. Lower Eocene deposits in the Sacramento Valley, overlying the Paleocene Martinez formation or older rocks, are assigned to the Capay and the Meganos formations, and those in the northern San Joaquin Valley are assigned to the upper part of the Lodo formation or its correlatives and to the Yokut sandstone or correlatives. No early Eocene deposition is recorded in the southern San Joaquin Valley south of the Bakersfield arch, a paleogeographic situation inherited from the Paleocene.

Lower Eocene rocks of the Sacramento Valley are present over a larger area than Paleocene rocks. They are exposed on the west side of the valley, where they overlie Cretaceous rocks, and seem to be present in most of the valley as far north as Chico. From Chico southward at least 40 miles the major part of the lower Eocene section is confined in a deep narrow subsurface gorge (Frick, Harding, and Marianos, 1959). (See fig. 5, "Capay gorge.") The older Eocene rocks of the Sacramento Valley are all referred to the Capay formation except in the Mount Diablo area and nearby subsurface sections. Here (fig. 3, column 6) rocks apparently equivalent to the Capay are called the "E" shale member of the Meganos formation (Clark, 1921a, p. 187). This is the type area of the Meganos and seems to be the only place where rocks of early Eocene age are included in the Meganos. Elsewhere, the Meganos is believed to be entirely Paleocene and to underlie the Capay formation. The Capay formation, including the "E" shale member of the Meganos, is composed of greenish-brown to gray fetid shale with phosphatic nodules and beds containing disseminated authigenic pyrite. These rocks suggest deposition in a basin with little circulation to the open sea and very
stagnant bottom conditions. In some areas the Capay contains a glauconitic sandy conglomerate at its base.

In general the Capay formation thickens westward; it is thickest at the type section (fig. 3, column 1) near the town of Capay, where Crook and Kirby (1935) report 2,500 feet. In the area north of Mount Diablo the "E" shale of the Meganos (equals Capay) is about 1,200 feet thick.

Throughout the central Sacramento Valley, however, the Capay is between 300 and 400 feet thick, except within the buried gorge, which it fills to depths as great as 2,000 feet (Frick, Harding, and Marianos, 1959). The Capay is generally thinner along the eastern edge of the valley and contains sandstone units, as the Dry Creek sandstone member (or "formation" where the remainder of the Capay is missing) (fig. 3, columns 3 and 4).

The relation of older Eocene rocks in the San Joaquin Valley to the Capay formation in the Sacramento Valley is uncertain. They are now discontinuous in the subsurface across the Stockton arch. South of the arch the rocks in the upper part of the Lodo formation are generally similar lithologically, but contain a higher proportion of sandstone and less material suggesting a stagnant marine environment. These differences suggest a barrier between the two basins, with the northern Capay basin having a more constricted connection to the sea than the southern Lodo basin.

In the San Joaquin Valley the Lodo formation is composed of siltstone and claystone with some interbedded sandstone. Its lower member, the Cerros shale, is highly glauconitic and sandy in its lower part but otherwise is quite similar to the upper member of the Lodo—the Arroyo Hondo shale member. In parts of the northern and western San Joaquin Valley, the two shale members are separated by the Cantua sandstone
member, a medium- to coarse-grained sandstone containing iron-stained concrections up to 7 feet in diameter. Locally the Cantua member is as much as 4,500 feet thick (White, 1940, p. 1740). Where the Cantua is absent, the two shale members of the Lodo are inseparable. The Lodo formation has a maximum outcrop thickness of about 5,000 feet but is less than a thousand feet thick in most areas. It is thickest in its westernmost exposures and, like the Capay, thins eastward toward the central part of the northern San Joaquin Valley. Most of this eastward thinning is a result of the loss of the older parts of the Lodo, and in these areas the Arroyo Hondo member of the Lodo is often referred to formational rank (fig. 3, columns 10 and 11). Because of truncation by the Domengine or younger formations, the Lodo formation is not present in the eastern half of the northern San Joaquin Valley.

The Yokut sandstone (White, 1940, p. 1746) overlies the Lodo formation and is also cut by the pre-Domengine unconformity. It occupies a position comparable to the Dry Creek sandstone member of the Capay. It crops out only along the western side of the San Joaquin Valley between Coalinga and the Panoche Hills, where it is less than 200 feet thick. Eastward, toward the center of the valley, the sandstone thickens beneath the pre-Domengine unconformity to as much as 800 feet and is known as the Gatchell sand. The Gatchell sand intertongues with, and apparently is locally replaced by, the Arroyo Hondo shale member of the Lodo. It is the oldest oil-producing unit in the Tertiary section of the San Joaquin Valley.

The Gatchell sand is a light-pink to nearly white, medium- to coarse-grained, clean, quartzose sandstone. It contains interbedded claystone and mudstone which become increasingly abundant toward the areas
where the Gatchell intertongues with the Arroyo Hondo member. It may be equivalent to the Tesla formation to the north, which has a maximum thickness of nearly 2,000 feet (Huey, 1945) (fig. 3, columns 8, 9, 10, and 11).

The Tesla formation pinches out along the outcrop northward near Mount Diablo and is overlapped by Miocene units. According to Huey it is a white, fine- to medium-grained, well-sorted, massive to thinly bedded, friable sandstone interbedded with coal. It is composed of about 75 percent angular quartz and 10 to 30 percent feldspar. Beds 15 to 20 feet thick have been mined in the Livermore area as a source of glass sand.

Huey notes that the Tesla formation, although containing fossils believed to be equivalent in age to the Lodo formation and the Yokut sandstone (Capay "stage"), is strikingly similar to the Domengine formation, which crops out along a 20-mile belt on the northeast side of Mount Diablo. One 60-foot bed of this Domengine unit has been mined for glass sand and is a white, fine-grained, well-sorted, compact, quartz-rich sandstone. It may be an extension of the Ione formation from the eastern part of the Sacramento Valley.

The older rocks of the Central Valley Eocene section are separated from the younger Eocene rocks by a pronounced unconformity. In the Sacramento Valley this unconformity is at the base of the Ione formation or its correlatives, or beneath younger units that overlap the Ione. In the northern part of the San Joaquin Valley the unconformity is at the base of the Domengine sandstone or beneath younger units which overlap this formation near the margins of the basin. The younger Eocene rocks were deposited across the Bakersfield arch and throughout the southern San Joaquin Valley (fig. 6). The similarity of rock types on either side of the Stockton arch suggests that during late Eocene time this positive
Distribution and thickness of upper Eocene sediments at the beginning of Oligocene time in Central Valley of California.

**EXPLANATION**

- **MARINE DEPOSITS**
- **CONTINENTAL DEPOSITS**

Heavy line shows present limits of sedimentary rocks in the Central Valley.

**SCALE IN MILES**

0 10 30 50

**SOURCES**

**NORTH OF STOCKTON ARCH**
- Several sources but information approximate.

**SOUTH OF STOCKTON ARCH**
- Hoots, Bear, and Kleinpell, 1954a, with some change.

**FIGURE 6.** Distribution and thickness of upper Eocene sediments at the beginning of Oligocene time in Central Valley of California.
area was not an effective barrier, and the absence of late Eocene rocks may be due entirely to subsequent uplift and erosion prior to Miocene deposition.

In the Sacramento Valley the Ione formation is nearly as extensive as earlier Eocene rocks, but it crops out only along the eastern side of the valley. This unit is a poorly consolidated, nearly massive, quartzose sandstone with a high percentage of interstitial clay. It has been mined locally for glass and for clay. The Ione is present throughout the central part of the Sacramento Valley and grades eastward into the Butte gravels which crop out along the eastern edge of the valley and overlie the granitic basement of the western slope of the Sierra Nevada (fig. 3, column 3). The formation is about 200 feet thick throughout most of the area. It is locally overlain by shale, which is treated as part of the formation or as undifferentiated Eocene. Near Mount Diablo the possible Ione equivalent is interbedded with coal and is about 500 feet thick.

Except for the overlying shale locally present in the central Sacramento Valley, younger Eocene rocks are absent, and the Ione is unconformably overlain by a thick sequence of volcanic rocks of questionable Oligocene and Miocene age and by continental beds of probable Pliocene age. The Ione therefore represents the last known marine invasion of most of the Sacramento Valley. Younger marine beds, however, are present in the southern part from the Mount Diablo area eastward nearly to the Sierra Nevada.

In the area north of Mount Diablo the younger Eocene rocks include, in ascending order, the Domengine formation, the Nortonville shale, and the sandstone and shale of the Markley formation. The Domengine formation is about 1,000 feet thick and consists of a lower shale and coal unit, 500 feet of sandstone already mentioned as a possible equivalent
of the Ione, and an upper shaly sandstone. The Nortonville consists of about 500 feet of gray to dark-brown claystone with silty or sandy units and a few lenticular sandstone beds. It ranges from 50 to 500 feet in thickness, with a gradual decrease eastward to within 20 miles of the eastern edge of the Sacramento Valley, where it is truncated by the unconformity beneath the Valley Springs formation of Miocene age.

The Markley formation is more than 3,000 feet thick near Mount Diablo and is composed of about three-fourths sandstone and one-fourth shale. It has been divided into a lower 2,000-foot sandstone member, a medial shale unit about 700 feet thick, and an upper sandstone unit about 500 feet thick (fig. 3, column 6). The sandstone units are gray, very micaceous, medium grained, and carbonaceous. The shale units are gray to brown and contain silt, clay, and carbonaceous material. The Markley thins uniformly eastward from Mount Diablo beneath the Oligocene Kirker formation to about 200 feet in the central part of the valley and maintains this approximate thickness eastward to the point where it is truncated by the Valley Springs formation near the eastern edge of the valley. Taff (1935, p. 1092) referred the medial 700-foot shale member of the Markley in the Mount Diablo area to the Kreyenhagen shale, with which it is undoubtedly correlative.

Apparently the Nortonville and Markley formations are of limited extent in the Sacramento Valley. As typically developed marine units they seem to be restricted to only the southern end of the Sacramento Valley. Possibly they were at one time continuous with the Kreyenhagen shale of the San Joaquin Valley, but they are now separated from it by subsequent erosion across the Stockton arch. Possibly they contain correlatives of the Wheatland formation or of the volcanic rocks.
overlying the Ione farther north in the Sacramento Valley.

In the San Joaquin Valley the younger Eocene rocks represent a fairly complete cycle of basin deposition. Initial invasion of the sea following (or producing) the pre-Domengine unconformity was accompanied by the deposition of the conglomeratic sandstone of the Domengine formation. At the same time or earlier, the Uvas conglomerate member of the Tejon formation was deposited south of the Bakersfield arch (fig. 3, column 16). The relation between the Domengine and the lower part of the Tejon is uncertain. If at one time part of a continuous unit, their connection would seem to have been along the western side of the valley in the area of thickest sedimentation. However, present evidence suggests that the Domengine was restricted to the area north of the Bakersfield arch and that the older part of the Tejon was restricted to the extreme southern end of the valley. Subsequent Eocene deposition covered the Bakersfield arch, and the earliest deposits across the arch (the Point of Rocks sandstone) have been interpreted as an ancient and thick regolith reworked by the marine transgression (Hoots, Bear, and Kleinpell, 1954a, p. 119).

The Domengine sandstone is a tan, medium- to coarse-grained, poorly sorted, arkosic sandstone. It usually contains thin gray claystone and siltstone beds and characteristically has beds of dark chert pebbles in its lower part. It is quite variable in thickness but is about 200 feet thick in most areas. It is thickest in the Mount Diablo area, where 1,000 feet of strata are assigned to the formation, and thins irregularly southward and southeastern. In the Coalinga area it has thinned to a 5-foot bed of siltstone with large angular chert pebbles (called the "grit zone"), but southward it thickens to about 1,000 feet.
in the Kettleman Hills area, where it is called the Avenal sandstone (fig. 3, column 10). Fifteen miles farther south, in the Devils Den area, it consists of about 300 feet of tan, coarse-grained sandstone with black chert pebbles. This variation in thickness may represent the irregularity of the erosional surface upon which the Domengine, and the correlative units, were deposited. The formation is present in much of the central and eastern parts of the valley north of the Bakersfield arch.

South of the Bakersfield arch the Uvas conglomerate member of the Tejon formation is composed largely of granite debris derived from the nearby Tehachapi and San Emigdio Mountains. It is of local extent and about 100 feet thick. The Uvas contains a marine fauna that was either contemporaneous with the fauna of the Domengine (Marks, 1941) or somewhat older (Mallory, 1959).

Conformably overlying the Domengine sandstone in much of the San Joaquin Valley is a thick, conspicuous, and widespread sequence of brown to white gypsiferous and diatomaceous shale called the Kreyenhagen shale. The Kreyenhagen is one of the most lithologically consistent units in the Tertiary section of the San Joaquin Valley. In general the lower two-thirds of the section is a brown siltstone and claystone interbedded with some medium- to coarse-grained sandstone which is increasingly abundant toward the base. In most areas the sandstone units contain grains of black and white chert and are widely referred to as "salt-and-pepper sandstone." The upper third of the formation is a near-white, highly diatomaceous and gypsiferous shale and diatomite. Outcrops along the western side of the valley range from 600 to 1,000 feet in thickness from the Kettleman Hills northward, and rapidly increase in thickness to more than 4,000 feet southward with the development of the thick Point of
Rocks sandstone in the lower sandy part of the Kreyenhagen. This extreme thickness is recorded in the Devils Den area (Van Couvering and Allen, 1943). Farther south, in the McKittrick area, and eastward across the valley the average thickness of the Kreyenhagen and Point of Rocks formations is about 1,000 feet. Toward the eastern edge of the valley these formations intertongue with, and are replaced by, undifferentiated continental beds usually called the Walker formation (fig. 3, column 15). In the Bakersfield area, the Kreyenhagen and Point of Rocks grade laterally into interbedded marine and continental beds called the Famoso sand. It, in turn, grades eastward into the continental Walker formation.

The Kreyenhagen and its equivalents extend across the Bakersfield arch into the southern basin of the San Joaquin Valley and are continuous with the Tejon formation. However, the Tejon is lithologically unlike the Kreyenhagen. It consists of medium- to coarse-grained sandstone (upper one-third) and firmly cemented gray siltstone with thin sandstone beds (lower two-thirds). The Tejon is about 3,500 feet thick and has been subdivided into four members (Marks, 1943) (fig. 3, column 16).

To the north of Pacheco Pass the Kreyenhagen becomes sandier and is correlative with the Nortonville and Markley formations of the Mount Diablo area. Taff (1935, p. 1092) separated the Sidney shale member from the Markley formation in the Mount Diablo area and called it Kreyenhagen. The overlying "upper Markley sand" he apparently included in the basal beds of his "undifferentiated Miocene."

In some areas the upper part of the Kreyenhagen is of Oligocene age, and in a few areas (fig. 3, column 12) the overlying and lithologically similar Tumey shale of Oligocene age is not differentiated from the Kreyenhagen.
Oligocene rocks.—Rocks of Oligocene age are not well represented in the Central Valley. In some areas they were eroded prior to Miocene deposition; some may be included with upper Eocene or lower Miocene strata because of uncertain faunal correlations with the type Oligocene of Europe.

Oligocene rocks are represented in the Sacramento Valley by the Kirker formation and possibly by the Wheatland formation, which is composed of andesitic debris (Clark and Anderson, 1938, p. 945) (fig. 7 and fig. 3, columns 4, 5, and 6). The Kirker formation was described by Clark (1918, p. 86-99) in the area north of Mount Diablo as consisting of about 400 feet of sandstone, tuffaceous sandstone, and tuff. It rests unconformably on underlying rocks, and the unconformity represents considerable erosion in some areas. For example, the "Markley gorge" north of Mount Diablo in the Sacramento Valley (fig. 7) is cut in rocks ranging from the upper Eocene Markley formation to the Cretaceous and is filled with Oligocene sediments (Almagren and Schlax, 1957) correlative with the Kirker formation.

The Kirker has been recognized as far southeast as the central part of the northern San Joaquin Valley (Forrest, 1943, pl. III) and may be continuous with the Tumey shale farther south. It may be correlative, at least in part, with the Wheatland formation known locally in the southeastern part of the Sacramento Valley and to the San Ramon formation in the Berkeley Hills. Little is known about the distribution of the Kirker, and most subsurface information in the southern Sacramento and northern San Joaquin Valleys is inadequate to separate possible Kirker correlatives from continental sandstone of younger epochs.

Oligocene rocks of the San Joaquin Valley include the Tumey shale, San Emigdio formation, parts of the nonmarine Walker formation, and in
FIGURE 7. Distribution and thickness of Oligocene sediments at the beginning of Miocene time in Central Valley of California.
some areas the upper part of the Kreyenhagen shale. These units seem to be represented in most of the San Joaquin Valley. They have been eroded from the Stockton arch and other local areas.

The Tumey shale is treated either as a separate formation or as an Oligocene part of the Kreyenhagen shale. It is present in most areas along the western and central parts of the San Joaquin Valley from near the Panoche Hills southward. In part of its outcrop area, the Tumey has a basal sandstone as much as 800 feet thick and an overlying shale unit as much as 700 feet thick. Where the basal sandstone is present, the Tumey is generally separated from the Kreyenhagen, partly because of its Oligocene age. The basal sandstone is present in the subsurface of the southwestern part of the valley and has been called the Oceanic sand (fig. 3, column 13).

The basal Tumey sandstone along the west side of the valley north of Coalinga is well cemented, dark brown, medium to fine grained, and somewhat conglomeratic. Southward the Oceanic sand is less conglomeratic, more friable, and although medium grained, it contains a higher percentage of silt. It may be correlative with the upper part of the Famoso sand in the southeastern part of the valley (fig. 3, column 15).

The Oligocene shale units, whether called Tumey or Kreyenhagen, intertongue with the variegated shale and sandstone of the Walker formation along the eastern margin of the valley, and toward the southern end of the valley the marine beds intertongue with the thick sandstone and siltstone of the San Emigdio formation, which may be nonmarine in part. Extensive nonmarine sandy units of Oligocene age (Simmler and Sespe formations) west of the San Andreas fault apparently represent continental facies similar to the Walker and parts of the San Emigdio
(lower part of the Tecuya formation) but are more closely related to the marine Oligocene of the southwestern part of the valley.

In the area from the Kettleman Hills north to Mendota, a shale unit is often distinguished from the upper part of the Tumey (or Kreyenhagen) shale and is called the "Leda zone." The contact of the "Leda zone" with the underlying Oligocene has been described as an erosional surface by some workers; however, the unit is considered as a part of a continuous sequence of Oligocene shale by others. The recognition of the "Leda zone" as a distinct unit seems to be largely due to the contained fossils, for which it is named.

In most areas of the Central Valley an erosional unconformity separates the Oligocene rocks from the overlying Miocene rocks. In the southern part of the San Joaquin Valley the unconformity is apparently represented by a period of erosion. Northward from the region of the Panoche Hills, however, the unconformity is marked by increased angularity, indicated by truncation of beds along the western, and particularly along the eastern, margins of the valley. Greater deformation is indicated farther north, in the area of the Stockton arch, where the pre-Miocene beds are truncated across the entire width of the valley.

Miocene rocks.--The Miocene deposits of the Central Valley show extreme lithofacies variation. Although lithologic variation is characteristic of Tertiary sediments in this area, the Miocene rocks far exceed older and younger deposits in interfacies complexity and the stratigraphic nomenclature is extremely complex.

In general the deposits of Miocene age include continental conglomeratic sandstone around the margin of the depositional basin, marine
conglomeratic sandstone of near-shore environment in intermediate areas, and marine "deep-water" shale and sandstone in the central part of the depositional basin. Continental beds are considerably more prominent in Miocene deposits than in rocks of earlier age.

Miocene rocks are characterized by an increase in granitic detritus from the Sierra Nevada to the east and by the introduction of Franciscan debris from the rising Diablo uplift to the northwest. Granitic source areas to the west of the San Andreas fault also became prominent at the beginning of Miocene time.

Earliest Miocene deposition was broadly similar to Oligocene deposition. However, the early Miocene seas inundated the area west of the San Andreas fault and adjacent to the southwestern part of the San Joaquin Valley where Oligocene continental deposition had taken place (fig. 8). Throughout Miocene time the seas extended westward from the San Joaquin Valley across the present trace of the San Andreas fault. This extension of the depositional basin contrasts with earlier paleo-geography, as does the progressive northward extension of deposition up the San Joaquin Valley and across the Stockton arch into the southern Sacramento Valley by late Miocene and Pliocene time. Throughout Miocene time the basin margins were changing because of essentially continuous tectonic activity in adjacent highlands.

Continental deposits of early and middle Miocene age were deposited along the southern end of San Joaquin Valley at the foot of the San Emigdio and Tehachapi Mountains, along the eastern side of the valley, and across its northern part from the Sierra Nevada to the Diablo uplift at least as far north as Sacramento. These continental beds are referred to the Tecuya formation in the southern end of the
FIGURE 8. Distribution and thickness of lower Miocene sediments at the beginning of middle Miocene time in Central Valley of California.

SAH FRANCISCO
-
-
o
SOURCES
NORTH OF FRESNO--
Several sources
SOUTH OF FRESNO--
Hoots, Bear, and Kleinpell, 1954a, with some modification.
valley and informally to the Zilch zone or formation along the eastern side and in the northern part of the valley.

The recognition of subdivisions within the continental beds is difficult and in some areas impossible from subsurface data. In much of the southern and eastern areas of the San Joaquin Valley the Tecuya and Zilch are inseparable from the Pliocene Chanaq formation. In the northern part of the valley the Zilch merges with the Valley Springs formation of middle Miocene and possibly older age. Probably the greatest thickness of these lower to middle Miocene continental beds is present at the southern end of the basin, where as much as 4,000 feet of the Tecuya formation accumulated near the foot of the Tehachapi and San Emigdio Mountains. Along the eastern side of the valley the Zilch has a maximum thickness of about 2,000 feet, but where inseparable from the overlying beds, the entire continental sequence of Miocene, Pliocene, and probably Pleistocene age is as much as 4,000 feet thick. South of Fresno the Zilch is about 2,200 feet thick but thins northward beneath younger Miocene units to about 400 feet south of Merced. Near here the younger Miocene marine units pinch out, and to the north the Zilch is inseparable from Pliocene and probably Pleistocene continental beds; the combined continental section is about 3,000 feet thick in the Merced area.

Locally thin continental units, informally assigned to the Zilch, are present along the west side of the valley, as in the Panoche Hills (R. G. Schenck, oral communication, 1959), but for the most part continental Miocene deposits are not well developed along the flanks of the Diablo uplift. Although continental beds of Miocene age (Caliente formation) are now present west of the southern end of the valley, these beds seem to have been derived from the San Emigdio and
Tehachapi Mountains and have since been displaced along the San Andreas fault from some area to the south or southwest of the San Emigdio Mountains.

The gross lithology of these continental beds is similar in all areas. They are tan to red coarse-grained sandstone and conglomerate. Red and green shale beds are interbedded with the sandstone in many areas, particularly those closest to marine intercalations. The continental units are coarsest, often a boulder conglomerate, near the source areas and are thickest in areas closest to the marine deposits. The principal source areas were mostly granitic, with increasing amounts of volcanic and, to the west, Franciscan debris present in the younger Miocene and Pliocene rocks.

Toward the central parts of the basin the continental sandstone units intertongue with, and are replaced by, near-shore marine sandstone and shale units. These near-shore sandstone and shale units are frequently assigned to the Vaqueros (lower Miocene) or Temblor (middle Miocene) formations. This assignment is based mainly on faunal differences rather than lithologic variation. Since interpretations of the faunas differ, rocks called Vaqueros by some people may be called Temblor by others. For example, Vaqueros has been used locally in the subsurface of the Coalinga-Kettleman Hills area and farther south (fig. 3, column 11); the name Temblor is more generally used, however, for the same rocks throughout much of the San Joaquin Valley.

The marginal marine or near-shore marine sandstone units of Miocene age in the San Joaquin Valley are mostly weakly cemented, medium to coarse grained, and somewhat conglomeratic. For the most part they are relatively clean, but toward the central part of the basin many become
increasingly argillaceous. The increase in argillaceous material forms "permeability barriers," and in some areas these lithologic variations have resulted in the accumulation of oil. The best known example of such a "permeability-barrier" oil trap is in the upper Miocene Stevens sand southwest of Fresno (Hoots, Bear, and Kleinpell, 1954b).

In some places these marginal marine sandstone beds occur as more or less isolated bodies surrounded on all sides by less permeable rocks. Typically they coalesce toward the basin margins with the more extensive continental sandstone units, and intertongue toward the center of the basin with marine shale. They are locally as much as 2,000 feet thick, particularly the lower Miocene Vedder sand and the upper Miocene Stevens sand in the thick Miocene section south of the Bakersfield arch, but more typically they are between 500 and 1,000 feet thick. The better known sandstone units included in this group are called "Vaqueros," "Temblor," Stevens, Vedder, Phacoides, Rio Bravo, Olcese, and Carneros (figs. 3 and 9). Some of these names are derived from the name of an oil field or from a characteristic fossil or fauna. Probably some are synonymous.

The marginal marine sandstone units are interbedded with shale units which range from 100 to 1,000 feet in thickness and which, in the central part of the southern San Joaquin Valley, aggregate as much as five-sixths of the total Miocene section. Locally the total Miocene thickness exceeds 12,000 feet and is more than 6,000 feet throughout the southwestern San Joaquin Valley. These shale units have many names, including Reef Ridge, McDonald, Antelope, Round Mountain, Freeman, Jewett, Fruitvale, Vedder, Devilwater, Gould, Salt Creek, Santos, and Media (figs. 3 and 9). They are all brownish mudstone, having an
FIGURE 9. Distribution and thickness of middle Miocene sediments at the beginning of late Miocene time in Central Valley of California.

SOURCES
NORTH OF MERCEDE--
Several sources
SOUTH OF MERCEDE--
Hoots, Bear, and Kleinpell,1954a, with some modification.
appreciable percentage of silt and variable quantities of fine sand. Some are siliceous. For the most part, thick sections of claystone are absent. These thick shale units have sometimes been considered members of the Monterey formation that is typically developed in the Coast Ranges west of the Central Valley.

The Santa Margarita sandstone of latest Miocene age is probably the most extensive and uniform marginal marine sandstone unit in the San Joaquin Valley. This unit was deposited at the time of the most extensive marine invasion and is correlative with the San Pablo group that was deposited during a marine re-invasion of the southern Sacramento Valley (fig. 10). Contemporaneous continental deposits, referred to the Valley Springs and Mehrten formations, were deposited across the Stockton arch at this time and perhaps some distance northward up the Sacramento Valley as the basal part of the Tehama formation.

The Santa Margarita is light-gray friable sandstone composed of poorly sorted, subangular, fine- to coarse-grained quartz, feldspar, and granitic fragments. Conglomeratic beds and many interbeds of sandy mudstone are common. It is quite variable in thickness and locally is as much as 2,000 feet thick; however, in most areas it is less than 1,000 feet thick. Toward the basin margins the Santa Margarita intertongues with continental sandstone units known as Bena gravel to the south and Zilch to the north. It is difficult to distinguish between these marine and continental units in subsurface sections. Toward the central parts of the basin the Santa Margarita intertongues with, and is replaced by, the McLure, Reef Ridge, and Antelope shales. The Stevens sand is a particularly extensive basinward tongue of the lower part of the Santa Margarita sandstone.
Sources

North of Merced—
Several sources

South of Merced—
Hoots, Bear, and Kleinpell, 1959a.

Figure 10. Distribution and thickness of upper Miocene sediments at the beginning of Pliocene time in Central Valley of California.
The Santa Margarita sandstone is present in the subsurface throughout most of the San Joaquin Valley except in the southwestern part between Coalinga and the San Emigdio Mountains. In this area it has been replaced by the Reef Ridge, McLure, and Antelope shales. Although widely distributed in the subsurface, it does not crop out in many areas. It is absent along the west side of the valley except between Coalinga and Tumey Gulch south of the Panche Hills. To the north it is truncated by Pliocene units and to the south it is replaced by shale units. Coarse conglomerate lenses in the McLure and its equivalents farther south at Reef Ridge and in the Temblor Range may be Santa Margarita tongues extending far into otherwise dissimilar lithology.

The Santa Margarita is not represented in outcrops along most of the east side of the San Joaquin Valley because of eastward gradation, in the subsurface, into the more marginal and largely continental Zilch formation. In the central part of the valley the Santa Margarita sandstone is present as far north as Merced. Here it is replaced by undifferentiated Miocene and Pliocene continental sediments.

The Mehrten formation and the underlying Valley Springs formation (equals Zilch farther south) were deposited across the Stockton arch and intertongue with marine formations of the San Pablo group at the southern end of the Sacramento Valley (fig. 3, columns 4, 5, and 6). They are typical continental conglomerate, sandstone, and shale units and are regionally distinguished by lithologic differences. The Valley Springs contains a high proportion of fragmental rhyolite and is devoid of the fresh andesite fragments found abundantly in the Mehrten. Where present, the rhyolite and andesite debris seem to be diagnostic. The Miocene part of the Mehrten formation east of Stockton
(near Colombia) lacks volcanic rocks and overlies the granitic basement of the Sierra Nevada. In such areas fossils seem to be the only means of separating the two formations.

The Mehrten formation is as much as 500 feet thick on the eastern side of the southern Sacramento Valley and the Valley Springs formation is about 450 feet thick. Here the overlying upper Pliocene and Pleistocene units (Laguna formation) are as much as 1,000 feet thick. In the subsurface of the central part of the valley from the Stockton area southward, the combined and undifferentiated Valley Springs, Mehrten, and younger formations are uniformly between 3,250 and 3,500 feet thick.

The Valley Springs formation seems to be correlative, and perhaps continuous, with rhyolitic tuffs of approximately Miocene age overlying the Wheatland and Ione formations of the eastern and central Sacramento Valley as far north as Marysville Buttes. The Mehrten seems correlative with the younger andesitic tuff of the same area. To the west the Valley Springs formation is replaced by the Cierbo sandstone in the Rio Vista gas field (fig. 3, column 5), and in the outcrop section north of Mount Diablo the Mehrten formation is replaced by the Neroly formation.

The Cierbo sandstone and the Neroly formation of the San Pablo group are the only marine Miocene rocks recorded in the Central Valley north of the Stockton arch (fig. 10). Although quite widespread farther west in the Coast Ranges, their extent in the southern Sacramento Valley is essentially confined to the area west of the Rio Vista gas field. The formations are composed largely of marine sandstone and conglomerate with minor amounts of shale. Many units are tuffaceous, and south of Mount Diablo the Neroly contains andesitic debris suggestive of the Mehrten formation to the east. Much of the sandstone of the Neroly formation is
colored a distinctive blue because of a "dull opaline coating on the grains" (Huey, 1948, p. 43). The Cierbo and Neroly vary considerably in thickness. Clark (1915, p. 406) reports about 600 feet on the north side of Mount Diablo and about 2,600 feet to the south of the mountain. Of this greater thickness Huey assigns about 500 feet of the lower part to the Cierbo formation and the remainder to the Neroly formation.

West of Mount Diablo and in the Berkeley Hills the marine rocks grade into thick continental beds (fig. 3, columns 6 and 7). This area lies within the structural belt of the Coast Ranges, and thickness, facies, and distribution of deposits are quite variable.

**Pliocene rocks.**—Tectonic activity in the Central Valley at the beginning of Pliocene time resulted in erosion in many areas, particularly along the western edge of the San Joaquin Valley. The erosional unconformity upon which Pliocene rocks were deposited is regionally almost as significant as the pre-Domengine unconformity and the unconformity above the Moreno shale. Economically it is more significant, for many of the oil fields on the west side of the San Joaquin Valley either produce from traps caused by the early Pliocene warping or from truncated reservoir beds sealed by later Pliocene deposition.

Considerable modification of the overall shape of the depositional basin also took place during this orogeny. The Central Valley assumed its present form; and Pliocene deposits, largely continental, are found in all parts of the valley. Regional elevation of the valley progressed throughout Pliocene time and marine deposition was restricted to the western half of the southern San Joaquin Valley (fig. 11).

The marine lower and middle Pliocene rocks of the San Joaquin Valley are described variously as the Etchegoin formation, the Etchegoin...
FIGURE 11. Distribution and thickness of Pliocene sediments at the beginning of Pleistocene time in Central Valley of California.

SOURCES
NORTH OF FRESNO--
Many sources

SOUTH OF FRESNO--
Hoots, Bear, and Kleinpell, 1954a,
with some modification.
and Jacalitos formations undifferentiated, or as the two formations differentiated. In the definition of the Jacalitos formation (Arnold and Anderson, 1910, p. 96), it was pointed out that the unit could not be separated from the overlying Etchegoin formation on the basis of lithologic or topographic individuality, but only on the basis of its contained fossils.

The Etchegoin formation, used in the broad sense to include the beds containing the lower Pliocene Jacalitos fauna as well as the middle Pliocene Etchegoin fauna, is composed of sandstone, conglomerate, and shale. The sandstone contains a high percentage of volcanic detritus and is brown, locally bluish, conglomeratic, generally quite silty, and is quite variable in grain size and sorting. The shale varies from a dark-green claystone to gray or brown pebbly mudstone. The Etchegoin attains a thickness of about 2,000 feet in the Coalinga area and thickens eastward to as much as 3,500 feet in the central part of the valley. East of the central part of the valley it rapidly intertongues with, and is replaced by, continental beds assigned to the Chama and overlying Kern River formations. In the central part of the basin the Etchegoin is present southward across the Bakersfield arch; northward from Coalinga it is most extensive along the western side of the valley and is reported nearly as far north as the Panoche Hills. Here it is truncated by overlying Pliocene and Pleistocene units, but in the central part of the valley it grades northward into continental beds equivalent to the upper part of the Mehrten formation and to the Laguna formation.

The most extensive marine unit of the Etchegoin formation is the Macona zone or shale, named from the fossils abundantly present in it. It extends well eastward of the main body of the Etchegoin in the
Bakersfield area (fig. 3, column 15) and is used there to separate the lower Pliocene Chanac formation from the overlying Kern River formation. Where the Macoma shale is absent it is impossible to separate the Chanac from the Kern River formation, and one or the other name is applied to the entire sequence, which ranges from 1,000 to 2,500 feet in thickness.

Overlying the Etchegoin formation, and also grading into the Kern River formation in the southeastern part of the San Joaquin Valley, is as much as 2,000 feet of mudstone, sandstone, and muddy conglomerate called the San Joaquin formation of latest Pliocene age. In the Coalinga and adjacent areas the San Joaquin formation is partly of marine origin and consists mainly of claystone, siltstone, and silty sandstone. This fine-grained lithology persists in the western and central parts of the valley as far south as the Bakersfield arch and nearly as far north as the recognizable Etchegoin. Beyond these limits the San Joaquin grades into continental sand and gravel—Chanac to the south, Kern River to the east, Laguna to the north. Northward along the west side it is either replaced by the Tulare (?) formation of Pleistocene age or is absent in the outcrop.

The base of the Tulare formation is customarily placed at the top of the highest marine bed. In areas marginal to the main Pliocene marine basin, this boundary may be variable, and part of the Tulare may be equivalent to part of the San Joaquin formation. In some areas the Tulare contains Pliocene fossil mammals.

In the area of the Stockton arch the Pliocene rocks include parts of the upper Miocene to middle Pliocene Mehrten formation and the middle Pliocene to probably Pleistocene Laguna formation. The Laguna is largely an unconsolidated fluvial deposit consisting of silt, clay,
medium- to coarse-grained sand, and lenticular gravel. In the type area northeast of Stockton (Piper and others, 1939, p. 57), it does not exceed 500 feet in thickness. To the west in the more central part of the valley, it has not been differentiated from the underlying Mehrten formation or the overlying fine-grained Pleistocene units. In the Stockton arch area the upper Miocene Pliocene, and Pleistocene continental section is at least 3,000 feet thick.

In the western part of the southern Sacramento Valley, north of Mount Diablo, outcrops of continental beds apparently continuous with the Laguna formation to the east range from middle to late Pliocene in age. These beds are locally as much as 1,000 feet thick and have been called the Wolfskill formation. They overlie a middle to lower Pliocene tuff unit called the Pinole tuff or, locally, the Lawlor tuff. In this area the tuff overlies the upper Miocene Neroly formation or older rocks and thickens westward to about 1,000 feet near San Pablo Bay.

Fifteen miles north of the type section of the Wolfskill formation, at the northern edge of Solano County, a similar section has been mapped as the Tehama formation. Here, as in most other areas, the Tehama overlies a widespread tuff bed called the Nomlaki tuff. Although the Pinole (Lawlor) tuff pinches out along the outcrop 7 miles south of the type section of the Wolfskill and is thus separated from outcrops of the Nomlaki tuff at Capay by a distance of 22 miles, the two tuff beds may be correlative. However, Anderson and Russell (1939, p. 250) feel that the tuff at Capay is not the Nomlaki tuff, because of differences in composition.

The Tehama formation is present throughout the Sacramento Valley and is as much as 2,000 feet thick. It is composed of light-colored
silty and sandy fluvial deposits with some gravel that becomes more abundant toward the source areas. The composition of the Tehama varies greatly with different source areas. On the eastern side of the valley it is usually called the Tuscan formation and is composed largely of volcanic debris derived from the Sierra Nevada to the east and Modoc Plateau area to the northeast. It is underlain by the Nomlaki tuff in the northern part of the valley. To the south along the eastern edge of the Sacramento Valley and away from the volcanic source, the Tuscan presumably inter-tongues with rocks lithologically similar to the contemporaneous Laguna formation, although the name Tehama formation is customarily used for such lithology except in the extreme southern end of the Sacramento Valley.

**Pleistocene rocks.**—Rocks of Pleistocene age are present throughout the Central Valley of California. They are all of continental origin and, except locally along the margins of the valley, they are not differentiated from the underlying upper Pliocene formations. Two units are recognized at opposite ends of the Central Valley. The Red Bluff gravel, recognized in the northern part of the Sacramento Valley, is a coarse fluvial formation of bright-red color that is less than 100 feet thick in most areas. The Tulare formation, recognized in the southern half of the San Joaquin Valley, is both lacustrine and fluvial. Along the margins of the valley it grades into coarse fluvial deposits which are usually lumped with the Kern River or Chualar formations. Locally they are referred to the Tulare formation. In the central part of the valley the Tulare is as much as 3,000 feet thick. South of the Bakersfield arch and on the downthrown side of the White Wolf fault, it has a maximum thickness of more than 5,000 feet. The Red Bluff gravel is essentially flat-lying, but the Tulare and correlative deposits of the southern San Joaquin Valley
are deformed and indicate recent tectonic activity in the southern part of the Central Valley. Recent alluvium covers much of the lowland areas of the present-day valley.

**STRUCTURE**

The Central Valley of California is an elongated northwest-trending structural basin or trough formed by the westward tilting of the Sierra Nevada block against the eastern flank of the Coast Ranges. This has resulted in the relatively uniform slope of the basin floor westward to its deepest part, near and parallel to the eastern edge of the Coast Ranges (fig. 12, in pocket). Between the central axis of the basin and its western margin, the beds filling the depression are folded and locally faulted.

In the central part of the basin, the Stockton arch bisects the Central Valley and structurally unites the Diablo uplift of the Coast Ranges with the Sierra Nevada block. This arch had formed by Eocene time and was active at least until the end of Oligocene deposition. A similar feature in the southern part of the valley, the Bakersfield arch, probably formed the southern end of the basin until middle Eocene time, when it was overlapped and for the first time the area of deposition extended as far south as the present limits of the valley.

Deposition across the Bakersfield arch in late Eocene time covered the area between the arch and the Tehachapi and San Emigdio Mountains. Although this area has been a part of the San Joaquin Valley depositional basin from late Eocene time to the present, it developed into and has continued to be a structural basin distinct from the remainder of the valley. It contains no part that is analogous to either the westward-
tilted floor of the Central Valley or to the folded and somewhat faulted western side of the valley, but rather appears related to structural basins which formed in the Coast Ranges to the west in Oligocene and particularly Miocene time. These basins west of the San Andreas fault were offset northward by the fault by Pliocene time and were no longer continuous with the basin south of the Bakersfield arch (figs. 6 to 11).

On figure 12 the basin south of the Bakersfield arch is shown as the "southern basin;" the westward-tilted basement floor of the Central Valley basin is shown as the "Sierran slope;" and the western folded belt parallel to the Coast Ranges is shown as the "folded trench." The division between the Sierran-slope and the folded-trench structural elements has been drawn at the axis of the major synclines which form the deepest part of the structural basin. This seems to be the approximate boundary between relatively unfolded strata with a prevailing westward dip and folded strata with a general eastward dip. Although most of the Central Valley is covered by Recent alluvium that conceals the structure in many areas, this distinction between the major structural elements fits the known information.

The Sierran-slope and folded-trench elements may be further subdivided at the Stockton arch on the basis of somewhat dissimilar structural history; the Sierran slope and folded trench of the San Joaquin Valley are more complex and varied than these structural units in the Sacramento Valley.

In the Central Valley four major periods of tectonism are recorded: the post-Moreno, the pre-Domengine, the pre-Pliocene, and the mid-Pleistocene periods of deformation. During these structurally active periods the major changes in the configuration of the depositional basin
took place and the majority of folds within the sediments were formed. The mid-Pleistocene period is considered by many to have been the most severe, and during this time apparently all flexures in the Central Valley were either formed or accentuated from older existing structures. Locally mid-Pleistocene warping produced a structural relief as great as 5,000 feet. Local areas were structurally active at other times throughout the Mesozoic and Cenozoic.

The recency of major tectonic activity in the Central Valley is not surprising in view of historical seismic activity. Figure 13, taken from Richter (1959), is an estimate of probable maximum seismic intensity to be expected in the Central Valley and other parts of California. It is based on the known geology in the area, tempered by historic records of seismic activity. In view of the proportionate briefness of the historic record as compared with the total time represented by the modern structural pattern, it must be admitted that the seismologic sample is quite small and statistically uncertain.

The evaluation of earthquake sensitivity of the Central Valley varies with depth as well as with area. The distribution of areas of probable intensity on figure 13 is largely based upon surficial rock types. Unconsolidated sediments are markedly more sensitive to seismic disturbance than consolidated rocks. If considered from the standpoint of conditions at a depth of about one mile, where consolidated rocks are more prevalent, nearly all of the area would be included in the VII maximum intensity scale, or less, except for the southern end of the San Joaquin Valley. This area, essentially the southern basin south of the Bakersfield arch, is composed largely of poorly consolidated Pliocene and Pleistocene sediments at this depth. In addition the southern basin is partly encompassed
FIGURE 13. Probable maximum seismic intensity of the Central Valley and adjacent areas of California.
and crossed by fault zones that are known to be active. The southern basin, therefore, is estimated as having a probable maximum seismic intensity of VIII or occasionally IX even at a depth of one mile.

WASTE DISPOSAL POSSIBILITIES

The safe storage of liquid radioactive waste in subsurface reservoirs is a complicated subject. Although geology is unquestionably one of the most important considerations, alone it is not adequate basis for even suggesting favorable storage environments. In the following discussion more or less untested assumptions have been made in order to provide a foundation upon which the geologic evaluation may be constructed. Without these assumptions the geologic analysis has no purpose or direction. These assumptions are as follows:

1) Permeable formations may be used for waste storage. This assumption is subject to many doubts and qualifications. (See Roedder, 1959, for example.)

2) Artificial reservoirs may be created in impermeable rocks by hydraulic fracturing or deep underground explosion. The use of such reservoirs for radioactive waste is untested although studies and tests on a small scale are in progress at Oak Ridge National Laboratories.

3) The quantity of waste to be disposed of is not considered great relative to the capacity of the geologic reservoirs under consideration. This assumption can be only partly true and its evaluation must wait for more specific information regarding quantity of waste and study of specific
storage reservoir capacity. Roedder (1959, p. 17) suggests that within a comparatively few years, a daily output of 100,000 gallons of high-level waste for the entire United States is a reasonable assumption. With quantities of waste as large as this, reservoir capacity will need to be carefully determined before the investment in a disposal plant is made.

4) Safe storage is understood to mean positive confinement for 1,000 years but is inferred to include slow migration, which, because of the time involved, loss of some radioactive components by becoming "fixed" through reaction with minerals within the reservoir, and dilution and dispersion while migrating, has remained within safe limits.

5) Optimum storage depth is one mile, which is well below the current water-supply level in the Central Valley. Storage only below the depth of potable water is considered. In general this will mean at depths greater than 2,000 to 3,000 feet.

6) The selection of a particular area or specific site for waste disposal cannot be made without very detailed geologic study. Because of the hazard involved, the detail of the geologic investigation must be far greater than most subsurface studies so far made for oil. The considerable cost and time involved discourages study in randomly selected areas and favors a joint reactor site-disposal site study program. This report does no more than point out that possibilities for waste disposal do exist in the subsurface rocks of the Central Valley of California.
content would be of considerable value because part of the radioactive components would be adsorbed by ion exchange. In the extreme southern end of the Sacramento Valley, in the area just north of the Stockton arch, the sandstone units of the Meganos formation, and particularly the Domengine sandstone, are of potential use in that they are permeable and are isolated by marine shale units. Also of possible use are sandstone beds of the Kirker formation, particularly where they fill the "Markley gorge."

Pleistocene and Recent rocks in the Sacramento Valley are largely of continental origin and are considered to be of little use for liquid-waste storage. Although composed of coarse and permeable sandstone, these continental deposits are poorly consolidated and characterized by complex lithologic variation. It is believed that the migration pattern of liquid waste through such units would be very difficult to predict and would be uncontrollable for the most part.

In the San Joaquin Valley sandstone units of Tertiary age with potential storage capacity include the Cantua sandstone member of the Lodo formation, the Yokut sandstone and Gatchell sand, the Domengine and Avenal sandstones, the Oceanic sand and other sandstone units within the Kreyenhagen, and the many marginal marine sandstone units of the Miocene. Sandstone tongues and beds in the Etchegoin (including the Jacalitos) and Tulare formations may also be of use. As in the Sacramento Valley, use of continental beds in the San Joaquin Valley is generally considered impractical because of the probability of uncontrollable migration of waste. However, discrete tongues of continental beds within the marine section would be useful.

The thick sandstone and conglomerate beds in the southern basin at the foot of the San Emigdio and Tehachapi Mountain are of possible
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The thick sandstone and conglomerate beds in the southern basin at the foot of the San Emigdio and Tehachapi Mountain are of possible
interest. These rocks include parts of the Tejon, San Emigdio, and Tecuya formations. This area is, however, quite active tectonically; most major historic earthquakes in the Central Valley have centered here. The southern basin, therefore, is not considered further at this time.

Artificial reservoirs in shale units.--Artificial reservoirs in shale might be created in a few units, but in general thick bodies of shale are not as widely available as are sandstone reservoirs. Many of the predominantly shale units are interbedded with thin beds of sandstone which are believed to be permeable. Those units that seem to have low enough permeability and thickness for use with artificially created reservoirs are the Capay shale in the southern Sacramento Valley and south of Chico where it fills the deep gorge, the Lodo formation where thickest in the San Joaquin Valley east of the Panoche Hills, the Kreyenhagen shale in a large area across the central parts of the San Joaquin Valley, and the several shale units of Miocene age in the extreme southwestern part of the San Joaquin Valley, where they contain the fewest interbeds of sandstone.

In summary, potential reservoir rocks, of both permeable and impermeable types, are available at many localities within the Central Valley, and in some areas several potentially useful rock units are available at one site. The selection of areas geologically favorable for waste disposal, therefore, will be governed primarily by factors restricting the migration of waste.

Migration barriers

Barriers to the migration of liquid waste within rock units are of importance primarily to permeable reservoir storage. It is assumed
that waste stored in artificially created reservoirs formed in impermeable units will be permanently sealed in, and hence cannot migrate. As much of the waste is expected to be largely nitric acid or acid aluminum nitrate and heavier than water, a permeable reservoir bounded by impermeable units in a syncline seems, at first glance, to be an ideal environment for restricting waste migration. This is an oversimplification, for account should be taken of the fact that the reservoir in which waste would be injected will be saturated with water which, if it is not already in motion because of pressure gradients imposed beyond the limits of the syncline, will start to move because of displacement by the injected waste and because of convectional currents generated by radiogenic heat. Both diffusion of the waste into the moving ground water and actual movement of the waste down gradient might take place. The simple synclinal structure therefore may be only of partial help in controlling waste migration; it may indicate the direction migration is most likely to follow.

A more certain means of restricting migration of liquid waste is by taking advantage of relatively impermeable barriers. Such barriers are present in reasonable abundance in the Central Valley of California and consist of facies changes within sandstone units such as those responsible for oil accumulation in the Stevens sand at the North Coles Levee field or in the Gatchell sand at the Coalinga Nose field. Permeability barriers also result from sandstone tongues that pinch out in impermeable shale units and from sandstone beds truncated beneath unconformities or against faults. These migration barriers are discussed by Hoots, Bear, and Kleinpell (1954b) in connection with the accumulation of oil.
Changes in permeability of sandstone units undoubtedly occur in most units and in many areas. The selection of the most favorable areas for such migration barriers will necessarily have to follow more detailed study. The same can be said of sandstone tongues which pinch out into impermeable shale units. Sandstone beds faulted and tightly sealed against impermeable units are believed to be the most uncommon type of migration barriers, although about 8 percent of the oil fields in the San Joaquin Valley obtain oil from fault traps and in an additional 25 percent faulting in combination with structure and (or) facies changes has trapped the oil. On the other hand the more or less continual structural activity during Tertiary deposition within the San Joaquin Valley area produced several widespread unconformities and many more of local extent; each truncates underlying beds. Migration barriers by truncated sandstone units are, therefore, quite common and occur mainly within broad belts along both the eastern and western margins of the valley. The western belt of truncated beds is also present in the Sacramento Valley but the eastern one is absent for the most part north of the Stockton arch.

These several natural migration barriers may well be combined to form suitable reservoirs with the desired degree of confinement for stored radioactive waste. In addition, artificial migration barriers may also be practical in some circumstances. Roedder (1959, p. 45-50) discusses possible methods for such artificial confinement of waste. As a means of eliminating precipitation of the waste, which would clog the reservoir pore space, acid treatment of the sandstone prior to waste injection has been suggested. The clogging effect of precipitation would operate as a migration barrier beyond the area of acid
treatment, and under suitable conditions could form an adequate, self-sealing barrier.

Other considerations

In addition to the control of waste migration, the selection of a disposal site should take into account what might be called accidental failure of confinement. Such failure might result from rupture of the reservoir by earthquake, leakage through improperly sealed wells that penetrate the storage reservoir, failure of injection equipment, or leakage from surficial installations such as storage tanks.

In general, the hazard of an earthquake producing a rupture in a sandstone reservoir bed seems remote except in the southern basin of the San Joaquin Valley. This area is very active tectonically. For other parts of the Central Valley, if a fault contact is considered as a barrier to fluid migration, the possibility of subsequent movement and the likelihood of leakage should be considered. It is also to be noted that surficial unconsolidated deposits react more severely to earthquakes, and it would be best, from the standpoint of the disposal plant equipment, to locate the disposal site within the areas of lesser seismic intensity probability as shown on figure 13.

In considering specific site locations, account should also be taken of the consequences of the accidental surface spillage of liquid waste at the disposal site. The geologic environment in which it would thus fall and steps that could be taken to contain it should be considered.

The disposal of radioactive waste within an area underlain by an oil or gas field is to be avoided because of the uncertainty of
completely sealing all of the previously drilled wells and test holes. Figure 14 shows the location of commercial oil and gas fields in the Central Valley and the approximate density of deep wells per township throughout the valley. In general, the eastern side as far south as Fresno and the extreme northern end of the Central Valley seem more favorable from the standpoint of minimum deep-well density, and the southern end and most of the western side of the San Joaquin Valley and the area between and west of Stockton and Sacramento in the Sacramento Valley is less favorable.

The regions of greater hazards from deep wells and from surficial seismic intensity roughly coincide (compare figs. 13 and 14). The location of areas with greater well densities also roughly coincides with thicker sections of basin fill, with the folded-trench structural element of the Central Valley, and with most of the areas in which thick impermeable units are present. This coincidence makes artificial reservoir construction in impermeable units seem less practical for waste storage.

Another consideration makes impermeable units seem less practical. Sandstone ordinarily has about twice the heat conductance of shale (Birch, 1954, p. 658) and thus would be more effective when considering dissipation of radiogenic heat.

In conclusion, the eastern side of the Central Valley of California, as far south as Fresno, seems to be the most promising area for the selection of a radioactive-waste disposal site. Here, south of the Stockton arch, the geologic environment to be sought is a thick sandstone bed tonguing westward into impermeable shale units and along its eastern end warped upward, truncated, and sealed by an overlying
Figure 14.--Oil and gas fields and well density of Central Valley.

Data from Oakeshott and others, 1952

EXPLANATION

1 to 5 wells per township

6 or more wells per township

Oil or gas field

Heavy line is boundary of Cretaceous and Cenozoic rocks within Central Valley.
younger shale unit. North of the Stockton arch westward-thinning sandstone tongues are less abundant and have not been warped and truncated to the east. A study of hydrologic conditions might reveal places where eastward migration would be slow enough to stay within safe limits.

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