HYDROGEOLOGY OF THE SUTTER BASIN,
SACRAMENTO VALLEY, CALIFORNIA

by

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STATEMENT BY AUTHOR

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ABSTRACT

A mound of saline water exists in continental sediments between two fresh water rivers in the Sutter Basin of the Sacramento Valley, California. This saline water has moved from the marine sediments, at depth, upward along the Sutter Basin Fault and then through 2,000 feet of alluvium.

The hydraulic head required to move the connate water is supplied by the high topographic position of the Cretaceous sediments carried up by the Sutter Buttes intrusives and exposed at the surface some 250 to 400 feet above the valley floor. Around the Buttes the marine sediments have been flushed with fresh water to depths of over 2,000 feet. The displaced saline connate water has moved south where it intercepts the Sutter Basin Fault.

The geologic section consists of about 5,500 feet of Cretaceous and Eocene marine sediments which have been deposited atop the basement complex (the western extension of the Sierra Nevada fault block) and capped by 2,000 feet of post-Eocene alluvium.

Chemical analyses of the ground water indicate sodium chloride water is being introduced from depth, and as the rising connate water moves northerly into the

orchard area it changes to a calcium-magnesium chloride type water.

INTRODUCTION

Purpose of the Investigation

When a mound of saline ground water exists between two fresh water rivers in alluvial sediments 2,000 feet thick, there must be an explanation. Two principal theories have been offered to account for the saline ground water mound that exists in the South Central portion of the Sutter Basin in California. Wilcox (1948) was the first to propose that the saline water was rising from depth. Wolfe (1958) advanced the theory that the saline water resulted from residual evaporites.

It is the thesis of this investigator that the salinity of the mound is due to the hydraulic head between the elevation of the Kione Sands, at their outcrop (recharge area) in the Sutter Buttes, and the elevation of the top of the saline ground water mound in the Sutter Basin. Fresh water has infiltrated and flushed the Kione Sands to depths of approximately 2,000 feet. The displaced marine connate water has moved south and rises along the Sutter Basin Fault, thence through the overlying alluvial sediments to the surface of the basin. A number of other geologic features are involved in the process.

The physical evidence to support the hypothesis was obtained through a study of the subsurface geology, the hydraulic continuity of the strata and structures and the chemistry of the water.

Maps display the strata, ground water hydrology and chemistry to support the statements that underly this thesis.

Location and Extent of the Area

The saline ground water mound with which this study is concerned lies north of the town of Robbins, California, in the middle of the Sacramento Valley, between the Sacramento and Feather Rivers. Under the saline ground water mound are approximately 2,000 feet of alluvial and non-marine basin sediments. The base of the fresh water that overlies the saline mound lowers in all directions from its center. The salinity of the ground water mound appears to increase with depth.

The area, generally known as the Sutter Basin, is bounded on the west by the Sacramento River, and by the Sutter Bypass on the east. It extends from the alluvial fans of the Sutter Buttes, some 30 miles southeast, to the confluence of the Sacramento and Feather Rivers. The basin lies wholly in Sutter County, California and consists of 114,500 acres of flat, topographical, low, poorly drained land.

To properly evaluate the ground water conditions of the Sutter Basin, the area of investigation was extended to include 1,026 square miles of land lying in all or part of

Township 10 North to Township 16 North, and Range 1 West to Range 4 East, Mount Diablo Base & Meridian. This includes parts of Colusa, Sacramento, Sutter, Yolo and Yuba Counties (Fig. 1).

Previous Investigations

The Division of Soil Management and Irrigation of the United States Department of Agriculture conducted a series of studies in cooperation with the Sutter Mutual Water Company during 1931, 1932, 1933, 1946 and 1947. These studies showed that the amount of dissolved solids in water drained from lands in the southern half of the Sutter Basin greatly exceeded the amount brought onto the land in irrigation water. The salt output during the study periods, expressed as proportion of the input, is reported to have ranged between 248 and 655 percent, with the average about 407 percent. It should be pointed out that all irrigation water for this area is diverted from the Sacramento River. The water table of the basin is controlled by extensive drainage ditches; the drain water is pumped out of the system back into the Sacramento River.

The investigator for the U. S. Department of Agriculture (Wilcox, 1948) concluded that the increase in salt content of the drainage water was due to rising connate water and said (pg. 48):

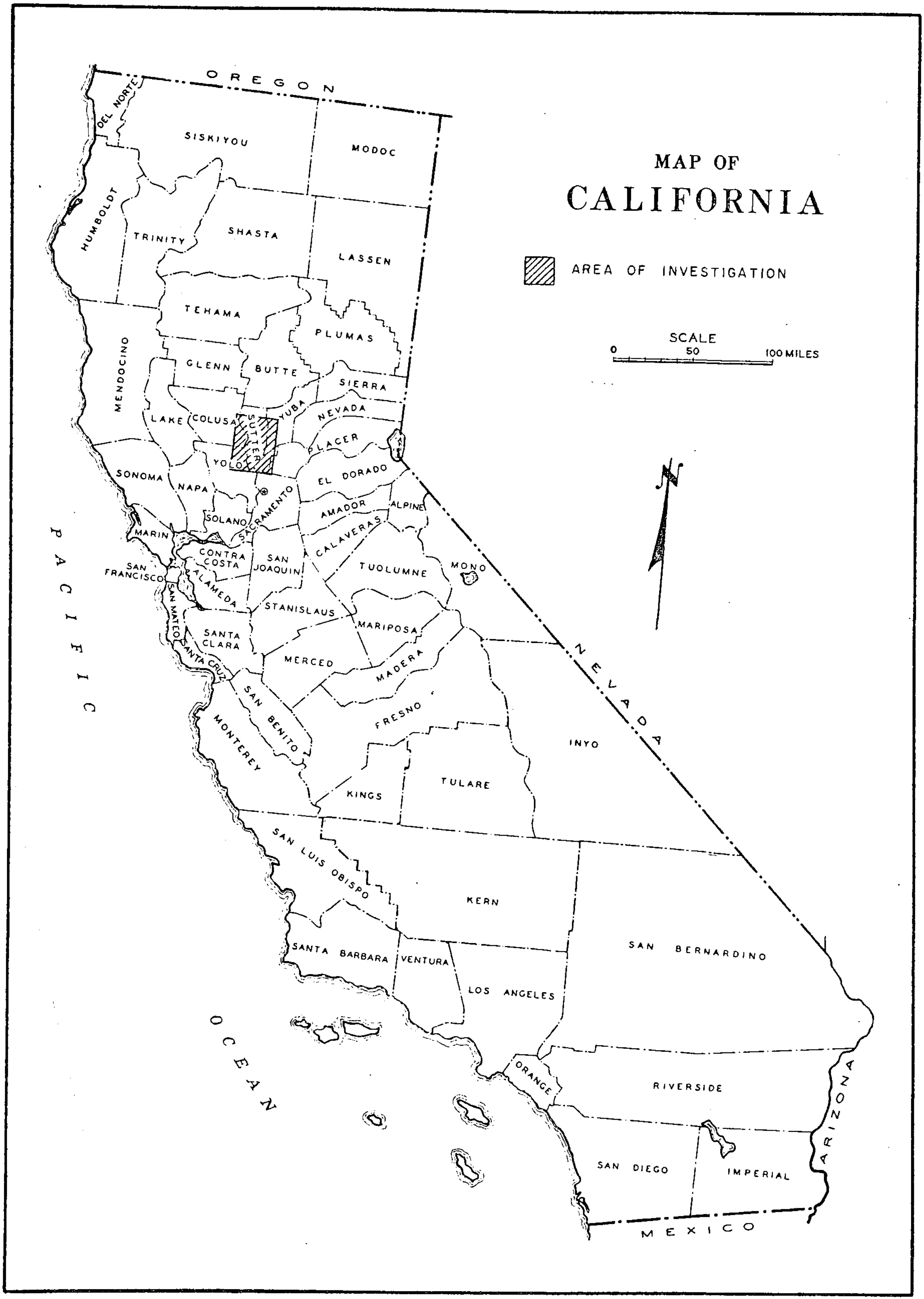

FIGURE 1 MAP OF CALIFORNIA SHOWING AREA OF INVESTIGATION

> Analyses show that the underground water is moderately to very saline, the lowest concentration observed being several times that of the input irrigation water. Also, all of the wells show a strong artesian pressure. Water in the domestic wells stands at or near the soil surface while the deep wells flow. It appears probable, therefore, that due to the upward pressure, substantial quantities of underground water are intercepted and carried off by the drains.

In September, 1952 the California State Water Resources Board published Bulletin No. 6, "Sutter-Yuba Counties Investigation." In this Bulletin reference is made to the Sutter Basin studies of the U. S. Department of Agriculture and indicates it is in agreement with the report as to the origin of these high chloride waters. Bulletin 6 states (pg. 35):

> The opinion was expressed in a report on the foregoing 1946 salt balance study that the salt in the drainage water was probably derived from saline waters underlying the area. Preliminary studies made by the Division of Water Resources similarly indicated that the chloride salinity in many of the wells was due to admixture of deep-seated brines with native fresh ground waters. There is evidence that such brines may underlie aquifers of good quality throughout large areas of the Sacramento and San Joaquin Valleys--such brines sometimes appear in water pumped from the deep wells in the two valleys, or from areas wherein the fresh ground water levels are markedly lowered through over-draft. In many instances these relatively deep-seated brines are under considerable pressure and readily rise to the surface through defective, abandoned, or improperly constructed wells. A case in point is a natural gas well located near the town of Robbins which yields water under artesian and/or gas pressure at a rate of 200 gallons a minute.

Included in the Resources Board's report was a geochemical study by Davis and Olmsted (1952) to determine the cause of the high saline water. A complete chemical analysis was run on water samples collected from 38 scattered wells located in Sutter Basin. The water analyses were classified into eight groups according to the range of concentration of total anions. Group 1 was considered unaltered normal ground water and Group 8 was considered briny contaminate. The chemical constituents, in e.p.m. (equivalent parts per million), of Group 1 were subtracted from the chemical constituents of Groups 2 through 7. The resulting chemical constituents, together with Group 8, were tabulated as to percentage. This tabulation indicated that (pg. 37):

> Irrespective of variations in concentration, the character formula of the degradant in each of the ground water Groups 2 through 7 is strikingly similar to that of the brines comprising Group 8. This is especially true of the anions which are not subject to base exchange reactions. This similarity in composition, together with apparent absence of any other like degradant, indicates that the degradation of the native ground water is due to admixture of deep-seated brines of the type exemplified by Group 8.

However, in the U. S. Geological Survey Water-Supply Paper 1497, Olmsted and Davis (1961, page 136) say:

> Its origin is problematical, however; it may be the result of upward migration of deep marine connate waters through defective, abandoned, or improperly constructed deep wells, as suggested by the California State Water Resources Board (1952, page 35); or, on the other hand, it may be merely a large body of evaporation residue in the Sutter Basin.

This conclusion is interesting because some nine years later these two geologists have added evaporation residue as an alternate theory for the occurrence of saline water in the Sutter Basin.

John Wolfe prepared an office report (Wolfe, 1958) for the California Department of Water Resources and summarized reasons for the theory of rising saline connate water as: (1) subsurface geologic structural highs in marine sediments; (2) artesian and/or gas pressure on connate brines which enable them to rise to the surface through poorly constructed or improperly abandoned water or gas wells; (3) artesian and/or gas pressure on connate brines which permit them to rise through permeable zones in the sediments; and (4) acceleration of rising connates due to lowering of the water table by heavy pumping.

Wolfe still believes (oral communique, 1969) that the geologic conditions favorable to the theory of rising connate water do not exist in the Sutter Basin, and brings forth the following points: (1) there is no known evidence of any structural anomalies in the Sutter Basin; (2) bad water conditions existed in the area before any deep wells were drilled; (3) the area is largely underlain by highly impervious silt and clay; (4) artesian pressure would not be augmented by gas pressure; and (5) an excess of salt and water in the discharge from a basin is no proof of rising saline connate waters.

Wolfe concluded that the saline water in the Sutter Basin is most probably caused by evaporative residues. He based his conclusion on the observation that salinity and well depth do not seem to correlate, and alkali or salts are known to accumulate in the basin sediments. To support his arguments he quoted Kirk Bryan (1923).

Kirk Bryan, geologist with the U. S. Geological Survey, conducted the first comprehensive ground water investigation of the Sacramento Valley. The field work for his water-supply paper was conducted during 1912 and 1913, a time when the Sacramento Valley was still subject to devastating floods and the basin lands were first being reclaimed and used for rice growing. Bryan (1923, page 85) commented on the accumulation of alkali in the Valley:

> Although there are in the valley large areas that have a shallow water table, which is favorable to evaporation and the accumulation of alkali, only comparatively small areas are unfitted for agriculture from this cause. This condition seems to be due to the following reasons: (1) The ground waters are of good quality. (2) The water table is very flat over the basins, and movements of the ground water are sluggish. Water is supplied more freely at the bases of the slopes, and for this reason the principal concentration of alkali occurs at the edges of the basins. This is particularly the case on the west side, where alkaline patches and areas of salt grass border the basins along their western edges. (3) The heavy winter rains leach out much of the salts concentration at the surface. Similarly flood waters wash out the salts in over-flowed lands, and on the edges of the plains the same waters deposit mud or sediment, which often covers up the alkali.

Bryan mentioned buried alkaline spots along the east side of Colusa Basin and suggested better water could be obtained by casing off the well and going deeper. He also suggested that the salty spots are usually small in extent. He thought the same conditions might exist along the west side of Sutter Basin.

In the east Sutter Basin area, Bryan spoke of Gilsizer Slough. This slough cuts southwest across the area from Yuba City to the central part of the Sutter Basin (Fig. 4). It is a depression that ranges in width from a hundred yards to a quarter of a mile. Bryan states that the ground water lay close to the surface and evaporation concentrated alkali in the soil. The slough was later drained by a ditch and the land reclaimed and placed under cultivation. However, the water quality of the wells in the Gilsizer Slough area seems to have been little affected by this shallow saline condition (Fig. 6).

History and Methods of the Investigation

During the early 1960s the California Department of Water Resources was conducting a comprehensive study of the ground water in the Sacramento Valley. Among the duties of this investigator was the compilation of a base-of-the-fresh-water map of the Valley. Electric-logs, run in gas wells, were used for the interpretive work. An apparent resistivity of 25 ohm-meters was designated as the dividing point between fresh and brackish ground water. Results of the study confirmed the mound of saline water in the central portion of the Sutter Basin; and further, that the Ione Sand of Eocene age contained fresh water to a depth of over 2,000 feet around the south central part of the Sutter Buttes. Elsewhere the Ione Sand contains saline connate water.

Correlation section #6, published by the American Association of Petroleum Geologists Committee on Stratigraphic Correlation, shows the stratigraphy of the Sacramento Valley from Red Bluff to Rio Vista. A portion of this section cuts across the Sutter Basin. On this section the Ione Sand crops out in the Sutter Buttes at an elevation of between 250 and 400 feet above the valley floor, is confined by the Nortonville Shale from the Buttes to Humble Oil and Refining Company's "Sutter Basin" #1 well in Section 24, T.13N., R.2E., M.D.B.&M. (well 201 on Fig. 4), and is in contact with the overlying continental sediments in the area of the saline ground water mound in the Sutter Basin. It was therefore believed that here were the conditions necessary for the hydraulic gradient requisite to move the saline water up through the nonmarine sediments to the surface in the Sutter Basin.

Permission was obtained from the Department of Geology, University of Arizona, to investigate this phenomenon as a thesis topic.

During the Summer of 1969 the author was employed by the California Department of Water Resources and permitted to use the office facilities during weekends and evenings to collect and analyze data. Some 550 gas well locations were plotted and electric-logs from more than 400 wells were collected and correlated. Further data were taken from the Department's detailed study of the water quality along both sides of the Feather River, 1964-67, as well as water analyses of wells made during the Department's regular yearly program for succeeding years. Part of this information is displayed graphically on Figure 6 (in pocket), the rest is contained in Appendix A.

Well-numbering System

The customary method of identifying gas and oil wells is to use the name of the operator and the name of the well. To be done legibly would require more space than is available on the base map used in this report. Therefore, each well was assigned a number. In general, the numbering began in Township 10 North, Range 1 West, and moved across to Range 4 East, etc. This places the low numbers in the lower left hand corner of the base map (Fig. 4, in pocket) and the highest numbers in the upper right hand corner. During the process of the investigation the size of the base map was reduced, so as to include only that area most relevant to the study; hence, not all of the wells originally numbered are plotted on the base map.

The water well numbering system used in the study is that of the California Department of Water Resources, and shows the location of wells according to the rectangular system for the subdivision of public land. For

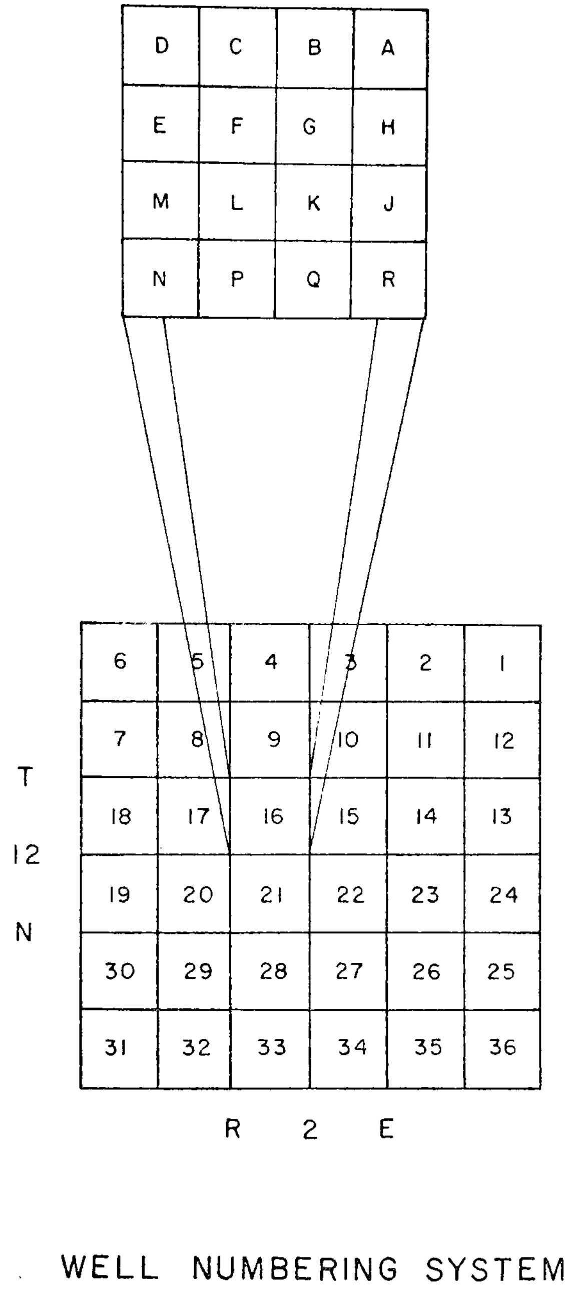

FIGURE 2 DIAGRAM SHOWING WELL NUMBERING SYSTEM

example, in well number 12N/2E-16B2, the segment of the number and letter preceding the bar indicates the Township (T.12N.); the number and letter between the bar and the hyphen, the Range (R.2E.); the digits between the hyphen and the letter, the Section (sec. 16); and the letter following the section number indicates the 40-acre subdivision of the section, as shown in Figure 2. Within each 40-acre tract the wells are numbered serially, as indicated by the final digit. Thus, Well 12N/2E-16B2 is the second well to be listed in NW1/4 NE1/4 Sec. 16, T.12N., R.2E., M.D.B.&M.

Parts of the study area lie in old Mexican land grants and have never been public land; for these, the rectangular system of subdivision has been projected for reference purposes only.

GEOGRAPHY

Topography

The Sacramento Valley is the northern one-third of the Great Central Valley of California and takes its name from the principal river which flows through it. The Sacramento Valley, as defined by Bryan (1923), extends from Red Bluff to the mouth of the Sacramento River at Suisun Bay, a distance of 150 air miles, or about 240 miles by river. The area of the Valley is approximately 5,000 square miles.

The Valley floor slopes southward from an elevation of nearly 300 feet at the north, near Red Bluff, to sea level at Suisun Bay and varies in width from five miles at the north end to 45 miles in the southern part.

The western boundary of the Valley is the North Coast Ranges, which consist of a series of parallel ridges and inter-montane valleys trending slightly west of north. The ridges rise to elevations of 3,000 feet.

The mountainous regions east and northeast of the Valley include the Sierra Nevada and the Cascade Range. The Sierra Nevada has been described (Lindgren, 1911; Matthes, 1930; Piper et al., 1939) as a single block of the earth's crust which has been uplifted along fractures on its eastern margin and tilted westward. The average slope of the western surface is $1^{\circ}40'$ and becomes steeper as it extends beneath the floor of the Sacramento Valley. The crest of the Sierra Nevada, to the east of the valley, varies from 6,000 to 10,000 feet in elevation. The Cascade Range, to the northeast, consists mainly of volcanic rock. It contains Mount Lassen, which is considered the only active volcano in California.

The Sacramento Valley has been divided into 16 geomorphic units by the U. S. Geological Survey (Fig. 3).

The study area for this report (Fig. 4) lies in the central portion of the Sacramento Valley. In this area the major topographic feature is the Sutter Buttes. It is the erosional remnant of a laccolith and volcano formed during late Pliocene time. The outline of the Buttes is an almost perfect circle, 10 miles in diameter, with the highest peak--South Butte--rising to an elevation of 2,117 feet. The only other prominent topographic feature is the Dunnigan Hills on the west flank of the Valley, which consist of Pliocene and Pleistocene sediments which have been folded into a gentle anticline with the axis trending approximately South 40° East. The Hills are severely dissected but the summits are rounded and rise to nearly the same height. The summits decline from an average altitude of 400 feet at the north end to about 200 feet near the south end.

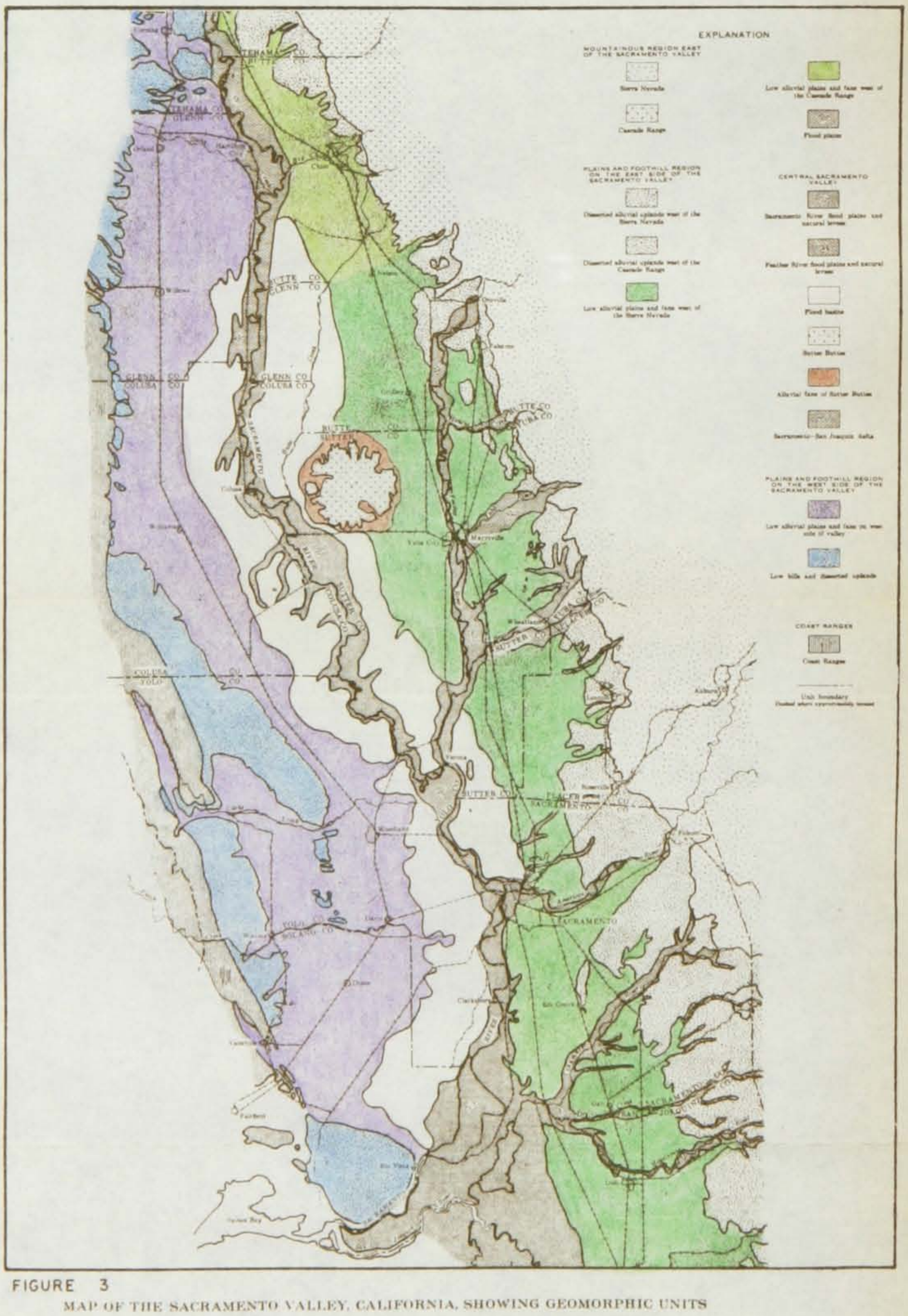

FIGURE 3

MAP OF THE SACRAMENTO VALLEY, CALIFORNIA, SHOWING GEOMORPHIC UNITS

SCALE 1:500,000
0 4 8 12 16 20 MILES

The other topographic features in the study area are of low relief and are related to the fluvial deposition of the Sacramento River and its tributaries. They include the alluvial fans on the west and east sides of the Valley and around the Sutter Buttes, the flood plains and natural levees and the flood basins. These fluviatile features have had a marked influence on the agricultural development of the area.

Drainage

The average annual runoff of the Sacramento River and its tributaries during a 40-year period starting in 1904 was 21,750,000 acre-feet. In the years past most of this flow took place during December to April. Only in the driest years was the Sacramento Valley free from flooding. During the wetter years the flood water would extend from the alluvial fans on the west side of the Valley to the alluvial fans east of the Feather River. Bryan (1923) estimated that before any reclamation had been accomplished, sixty percent of the Valley was subject to overflow--including, in addition to the basins, the river lands and a considerable portion of the low plains. In recent years the construction of levees along the major streams, flood-water bypasses through the Sutter and Yolo Basins, and the building of Shasta Dam on the Sacramento River and Oroville Dam on the Feather River, has greatly limited the large-scale flooding of the basins.

Between Colusa and Verona, the Sacramento River follows a sinuous course, with meanders and oxbow lakes. Over a distance of 63.5 miles the average descent is about 0.4 feet per mile. The channel is narrow--averaging 150 to 600 feet in width--with well-defined broad natural levees. The natural levees are concave upward and relatively flat. In effect, the river is flowing along a broad upraised trench, flanked on either side by poorly drained, low-lying flood basins. The Colusa Basin lies to the West, and the Sutter Basin to the East.

South of Verona at the mouth of the Feather River, the aspect of the Sacramento River changes completely, and the course of the river consists of broad, gentle bends and relatively long straight reaches. The channel averages 600 to 1,200 feet in width, and bars and islands are uncommon. The natural levees are well defined, but are generally narrower than those upstream; the belt of river lands averages about two miles in width.

The Feather River, the principal tributary of the Sacramento River, leaves the Sierra Nevada foothills at Oroville. It follows a southwesterly course for about six miles, then turns sharply south and flows across the Victor Formation of Pleistocene age. Upstream from Marysville, the Feather River flood plain is one to two miles wide and lies 10 to 15 feet below the adjoining low plains. The river pursues a meandering course on its flood plain, and lakes and abandoned channels are common features, indicating frequent changes in course.

South of Marysville, the Feather River is joined by the Yuba River, and in turn by the Bear River. Here the river occupies a broad channelway, as much as a mile wide, that is choked with sand and gravel contributed by the Yuba and Bear Rivers. This channel aggradation is a direct result of hydraulic mining in the Sierra Nevada.

In the seven-mile reach upstream from its junction with the Sacramento River, the Feather River occupies a channel ridge similar to that of the Sacramento River. The prominent natural levees slope a mile or more toward the Sutter Basin to the west, and the American Basin to the east. Well-formed channel ridges of flood distributaries extend laterally toward the flood basins, and bends and abandoned channels are noticeably absent, suggesting long-continued channel stability.

The average grade of the Feather River from Marysville to the Sacramento River is 1.1 feet per mile.

Climate

The climate of the Sutter area is characterized by dry summers with high daytime temperatures and warm nights, and wet winters with moderate temperatures. More than eighty percent of the precipitation occurs during the five-month period from November to March, inclusive. The eighty-year average precipitation for the City of Marysville is

20.68 inches, with an annual high of 38.91 inches and an annual low of 8.15 inches. The growing season is long, the forty-year recorded average for Marysville being 273 days between killing frosts. Temperatures at Marysville have ranged from 16°F. to 118°F., and the monthly average ranges from 46.9°F. in January to 79.3°F. in July.

Culture

The native vegetation in the study area consisted of grasses and occasional oak trees on the alluvial fans. The swamp and overflow land supported a heavy growth of tules, or rushes, that gave the area its coloquial name of the "Tules." The natural levees supported a heavy growth of trees, predominantly Sycamore and Cottonwood.

It was a natural step for the early settlers to substitute grain such as wheat and barley for the native grasses. The commercial production of wheat in this area was begun by General John Sutter in 1843 on his Hock Farm south of Yuba City. With the influx of settlers during and after the gold rush, a large portion of the higher land was converted to the growing of dry-farmed grain crops and livestock.

The continuing wave of settlers in the area caused an increase in land value and the subdivision of lands into small farms which had to be capable of producing consistently high-value crops in order to support the owners. To the purchasers of such tracts the advantages of irrigation were apparent. The colonizing of subdivided lands became a business whereby large blocks of land were purchased and surveyed into small tracts with provisions for roads and perhaps for a town site. Irrigation works were provided for some of the subdivided acreages; in others, a demonstration well and pumping plant was built to persuade the settlers of the advantages of installing their own individual wells and pumps. Settlers were attracted by agents and by advertisements in the eastern newspapers of the United States.

The development of the flood basin and overflow land was slowed by recurring floods. However, many public agencies were organized in the area to deal with the problems of land reclamation and drainage. The provisions of California reclamation district laws have been used extensively to effect the unwatering of low lands and their protection from overflow. A canal was excavated to remove the flood and drainage water from Colusa Basin. The function of Sutter Bypass is to receive and convey excess floodwater of the Sacramento River and Butte Basin through Sutter Basin (Fig. 4).

The highest and best use for most of the basin land, because of the heavy soil, is rice production. In 1966, some 66,000 acres of basin land in Sutter County alone, or one quarter of the entire County, were used for the cultivation of rice. The rest of the basin land is used mainly as irrigated pasture for the raising of livestock.

Other annual crops in the area consist of beans, tomatoes, safflower, corn, hops, sugar beets, and alfalfa seed. Along the Feather River the land is used mainly for deciduous orchards--peaches, apricots, pears, prunes, almonds and walnuts.

Industry in the area is supported largely by agricultural production. About 100 plants are operated during the harvest seasons to can fruits and vegetables and to dehydrate fruits, nuts, rice and seed crops. Packing houses for packing fresh fruits and melons, and cold storage and refrigeration plants, have also been placed in operation.

Following are the population figures for the three counties that comprise most of the study area, and the county seat for each.

	1960	1970
Sutter County	33,380	41,894
Yuba City	11,507	13,740
Yuba County	33,859	43,934
Marysville City	9,553	10,100 (est.)
Colusa County	12,075	11,896
Colusa City	3,518	3,825 (est.)

GEOLOGY

Stratigraphy

The west side of the Sacramento Valley contains one of the thickest and most nearly complete late Mesozoic sections in North America. The Upper Jurassic, Lower Cretaceous, and Upper Cretaceous sequences have a maximum aggregate thickness of sediments in excess of 50,000 feet (not illustrated).

The classification of the Upper Cretaceous by Kirby (1943), the Upper Cretaceous faunal zones of Goudkoff (1945), and the faunal zones of Laiming (1943) for the Paleocene and Eocene sediments have been used in this report (Fig. 5). Where there appear to be differences in opinion as to the stratigraphic relations of the subsurface geology, Correlation Section No. 6, 1954, "Sacramento Valley from Red Bluff to Rio Vista," of the A.A.P.G. Committee on Stratigraphic Correlations was used as the guide. Where this investigator differs from the A.A.P.G. Committee, these differences are based on electric-log interpretations and discussions with geologic consultants who have worked in the Sacramento Valley.

Upper Cretaceous Units

Forbes Formation. (Figs. 5 and 7, in pocket) The Forbes Formation is the basal member for sub-surface correlations illustrated, and has the most extensive distribution of any of the units correlated. It crops out along the western margin of the Sierra Nevada and along the eastern margin of the Coast Range. It is believed (Weagant, 1964) to have been deposited in a moderately deep-water environment, too far offshore to be affected by shoreline winnowing processes, and is the result of turbidity currents.

The thickness of the Forbes Formation varies from 2,750 feet to 3,000 feet in the study area. It is dominantly a gray, marine shale with fairly thick, fine-grained sandstone interbeds.

Kione Formation. (Figs. 5 and 7) The Kione Formation represents the shallowing of the Forbes basin, which resulted in the development of a shallow near-shore environment. The Kione sands were probably deposited in a series of deltas that lay at the mouths of the major drainages coming off the Sierran land areas to the east. These deltaic sands were further distributed along the east side of the valley by action of along-shore currents and by normal shoreline processes.

The Kione Formation was named and described by Johnson (1943). It is a medium-grained, well sorted, massive, friable sandstone of granitic origin with shale interbeds. The Kione is in gradational contact with the underlying Forbes Formation. Around the Sutter Buttes the

Kione has a thickness of between 800 and 1,000 feet. To the West, the Kione becomes more broken, tending to turn to shale, and to the south it thins and shales out. In the study area it is everywhere conformably overlain by the "Sacramento Shale", except in the Colusa area where it is reported to occur at a shallow depth and is overlain by the Tehama Formation.

"Sacramento Shale." (Figs. 5 and 7) This marine deposit has not been identified in outcrop, although it is possible that it crops out around the Sutter Buttes. For the purpose of this report it will be identified by the description as shown on A.A.P.G., Pacific Section, 1960, Correlation section from Red Bluff to Rio Vista, Sacramento Valley, "the siltstone which conformably overlies the Kione Sand and is conformably overlain by the 'Winter Sand'." The "Sacramento Shale" is typically 150 to 300 feet thick and light gray in color. It is everywhere present in the study area, and is an excellent electric-log marker.

"Winter Sands and Shales." (Figs. 5 and 7) The main source of the marine "Winters Sands and Shales" appears to have been older Cretaceous deposits, reworked and redeposited. In the Dunnigan Hills the shale is described (Rofe, 1962) as a medium-dull, gray, firm, massive, silty, muscovitic, fossiliferous claystone, grading locally into siltstone. The sand beds are light gray, fine to medium-grained, poorly sorted, massive, silty, micaceous sand with subordinate amounts of claystone that grade upward to well sorted, clean sand.

It is possible that the "Winters" crops out on the south side of the Sutter Buttes but has not been identified. It is not present north of the Buttes, it thins to the north and east, thickens to the south, and its western extent is obscured by uplift and erosion during post-Cretaceous time. The unit unconformably underlies the Starkey Sands in the area south of the Sutter Buttes.

"Starkey Sands." (Figs. 5 and 7) The "Starkey" represents a very shallow sea environment with deposition of a series of regressive-transgressive beach or near-beach sands. The deposits were derived from the east and northeast as the Sierran and northern Sacramento Valley areas were uplifted and eroded. The "Starkey" grades from a medium-grained, clean sand into a shale from east to west. The "Starkey" is everywhere confined by the Martinez Silt of Paleocene age or the Capay Shale of Eocene age, except in the southern Sutter Basin where it is unconformably overlain by the post-Eocene non-marine sediments (Fig. 7). The sand thins or has been removed by erosion to the north and west. To the south it occurs at ever-increasing depths and thickens to approximately 1,900 feet before thinning and shaling out in the Delta area.

Tertiary Units

Meganos-Martinez Formations Undifferentiated.

(Figs. 5 and 7) This group of sediments conformably overlies the "Starkey Sands" in the southeast portion of the study area.

The type locality of the Martinez Formation is near the town of Martinez on Carquinez Strait, west of Suisun Bay, and was described by Dickerson (1914). Lithologically, it is predominantly a massive, well-sorted, quartzose sandstone with interbedded shale and local conglomerate lenses. Much of the detritus of the Martinez was derived from Cretaceous Formations. A basal shale member is referred to as the Martinez Silt and is an excellent electric-log marker where it overlies the "Starkey Sand." The Martinez contains Laiming's (1943) E fauna zone and is Paleocene in age.

The type locality for the Meganos Formation is in Contra Costa County in the Mount Diablo region and was described by Clark (1918). It consists of friable, fine to medium-grained, micaceous, carbonaceous gray sand and hard, mostly light to dark brown shale with streaks of lignite. For the purpose of this report, it is considered to be those sediments containing Laiming's D fauna zone, and is Lower Eocene in age.

The thickness of the Meganos-Martinez group, in the study area, varies from zero to 240 feet. It occurs only in the south central portion of the study area where it is truncated or pinches out to the north and dips to the south.

Capay Shale. (Figs. 5 and 7) The type section for the Capay Formation is in Capay Valley, to the west of Dunnigan Hills, and was described by Crook and Kirby (1935). Unfortunately, the type section is atypical of most of the Capay in the Sacramento Valley. It consists of as much as 2,000 feet of beds resting unconformably on the Upper Cretaceous rocks, ranging from channel conglomerate to fine-grained estuarine deposits. The source of the detritus was said by Crook and Kirby to have been local. It is now believed that this part of the Capay was deposited in the southern extension of the Princeton Gorge. When the Eocene sea transgressed, the gorge was inundated first and coarse sediments were contributed from immediately adjacent sources. As the sea continued to rise, it topped the gorge and spread out over the floor of the Valley. It was then that the Capay Shale was so extensively deposited.

At Dunnigan Hills the Capay Shale is described by Rofé (1962) as medium gray to dark gray, massive, micaceous, glauconitic, pyritic, fossiliferous claystone with a dark gray, medium-grained, poorly sorted, massive basal gritstone, which is a more typical description of the Capay Shale and is probably the upper part of the Capay Formation. In the study area the Capay Shale is considered Lower Eocene in age.

The Capay Shale acts as a cap rock for many of the gas fields in the Valley. It is present throughout the area except where it has been removed by erosion in the Sutter Basin south of the Sutter Basin Fault, in the "Markley Gorge," and along the western margin of the study area. The Capay Shale varies in thickness from zero to 558 feet and thins to the East. The base of the Capay is one of the major unconformities in the Valley. The Capay progressively overlies older Cretaceous rocks in a northern and eastern direction.

Ione-Domengine Formation. (Figs. 5 and 7) Stewart (1949) divided the Domengine Formation of Clark (1926) into two formations: the Lower Ione Formation, consisting of quartz sand; and the Upper Domengine Formation, consisting of green and brown sand. Both are placed in Middle Eocene and contain Laiming's B-1 faunal assemblage.

In the Dunnigan Hills (Rofé, 1962), the Domengine Formation is 19 to 62 feet thick and consists of dark gray to greenish gray, fine-grained, well sorted, silty sands. It appears that the Lower Ione Formation of Stewart (1949) is not present at this location.

Throughout most of the area, the Middle Eocene is represented by the Ione Formation of Stewart. In the Sutter Buttes, the Ione is described by Johnson (1943) as a white, quartzose, friable sandstone, and probably represents deltaic deposits that have been winnowed by off-shore currents. Figure 5 indicates that the Ione-Domengine Formation is of rather limited extent in the study area, having been removed by erosion to the west and south. It ranges in thickness from zero to 250 feet.

The Ione-Domengine Formation conformably overlies the Capay Shale of Lower Eocene age and is conformably overlain by the Nortonville Shale of Upper Eocene age.

<u>Nortonville Shale</u>. (Figs. 5 and 7) Stewart (1949) divided the Kreyenhagen Formation of Upper Eocene age into the Nortonville Shale member, the Markley Sandstone member, and the Sidney Shale member, in ascending order. Only the Nortonville Shale has been identified in the study area, and then only in gas wells at Dunnigan Hills and in the Sutter Basin. The extent of the Nortonville sea is obscured by subsequent erosion, but probably did not extend further north than the Sutter Buttes and was not as widespread as the Capay sea.

In the Dunnigan Hills, the Nortonville Shale is described (Rofé, 1962) as blue and brown, firm, mottled, micaceous, sandy claystone, interbedded with grayish green, gritty sands. Its thickness varies from 92 to 235 feet, and contains Laiming's A-1 faunal assemblage.

"<u>Markley Gorge" Fill</u>. (Fig. 5) The "Markley Gorge," a deep canyon that was eroded during Upper Eocene, extends from north of the Bear River, near the foothills of the Sierras, southwest to the northflank of Mount

Diablo. This sub-surface feature is more than 45 miles long and nine miles wide, and reaches a maximum depth of 5,700 feet below sea level. Probably a better name for this feature would be the Sacramento Canyon, but at present it is referred to as the so-called "Markley Gorge."

Davis (1953) first described the Gorge, and believed that it was filled with Upper Eocene deposits. Almgren and Schlax (1957) believed the fill is Oligocene and, in part, possibly Miocene in age. Despite the later conclusions, most geologists with a working knowledge of the "Markley Gorge" Fill believe that it is no older than Late Eocene (Sacramento Petroleum Association, 1962).

The "Markley Gorge" Fill consists of shales, sandstone, and conglomerate which have considerable lateral and vertical lithologic variation. The shales are light olive-gray to grayish, brown, silty, and generally barren of microfauna. Sandstones are of two dominant types: one confined to the lower part of the fill is grayish green to greenish brown, earthy, poorly sorted and consists largely of grains of various volcanic rock types, and subangular to sub-rounded pebbles of gray shale and siltstone occur locally; the other dominant type of sandstone is blue, generally coarse-grained and fairly well sorted.

Post-Eocene Non-Marine Sediments. (Figs. 5 and 7) This classification is a catch-all for the alluvial sediments that have been deposited in the Valley by the

Sacramento River and its tributaries from both an eastern and western source. In the study area it has no commercial accumulation of gas and therefore is of little or no interest to the petroleum industry. Petroleum geologists usually call the entire interval the Tehama Formation, which does make up a large percentage of the sediments.

It appears that the Oligocene epoch was a time of uplift and erosion with little or no sediments being deposited in the study area. The Miocene epoch is represented by sedimentary rocks of volcanic origin. The rocks from the Sierra Nevada are a sequence of fragmental volcanic rocks, the source of which lay near the present crest of the Sierras, about 50 miles east of the Sacramento Valley. These rocks, predominantly andesitic, are extensively exposed on the western slope of the Sierra Nevada and extend westward beneath much of the Valley. They probably extend beyond the Sacramento River in the study area. This unit is believed to be related to the Mehrten Formation of Piper et al. (1939).

The sedimentary rocks of volcanic origin that crop out on the west side of the Valley are a sequence of volcanic shale, sandstone and conglomerate beds. Weaver et al. (1944) assigned most of these rocks to the Neroly Formation (Upper Miocene) of Clark and Woodford (1927), but their age and correlation are in considerable doubt.

Five wells (282, 291, 292, 293, and 296) have been drilled through a basalt flow that is approximately 150 feet thick. This island of basalt in Township 13 North, Range 2 East, is believed to be Upper Miocene in age and lies at the base of the Tehama Formation.

The Pliocene sediments consist of continental deposited Laguna Formation of Piper et al. (1939) and the Tehama Formation of Anderson and Russell (1939).

The Laguna Formation (not illustrated) is a sequence of predominantly fine-grained, poorly bedded, somewhat compacted continental sedimentary deposits derived from the Sierra Nevada. The Laguna appears to form a wedge of alluvial material thinning near the Sierra Nevada and thickening toward the axis of the Valley. The maximum thickness of these deposits may be more than 1,000 feet.

The Tehama Formation (Fig. 4) consists of alluvial material derived from the Coast Ranges. It was inaugurated by the orogeny at the beginning of Late Pliocene time, which raised the present Northern Coast Ranges, and was closed by a Middle Pleistocene orogeny. The Formation has been assigned to the Upper Pliocene and possibly the Lower Pleistocene by Anderson and Russell (1939). They state the Formation consists of poorly sorted fluviatile sediments, comprising massive sandy silt, silty sand, and clayey silt enclosing lenses of crossbedded sand and gravel.

The Tehama forms a thick wedge of sediments that thicken to the east and interfinger with the Laguna Formation beneath the Valley floor. In the study area, the Tehama Formation has a maximum thickness of approximately 2,500 feet.

The Sutter Beds of Williams (1929) which crop out in the Sutter Buttes are correlative to the Tehama Formation according to Johnson (1943). They are comprised of continental fine-grained sediments, tuff, sand, silt, and gravel some 1,800 feet in outcrop. Both Williams (1929) and Johnson (1943) believed that the Sutter Beds had a Sierran source because they are petrologically similar to the Sierran andesites. If this be true, then the Sutter Beds are better correlated to the Laguna Formation of Piper et al. (1939).

Quaternary-Recent Units

During Pleistocene time, some 1.2 million years ago, as indicated by radioactive dating according to Dr. Howel Williams (oral communique, 1969), a series of volcanic episodes--the intrusion of rhyolite porphyry volcanic necks followed by the intrusion of an andesite porphyry plug--resulted in the formation of the Sutter Buttes. The final igneous episode was the explosive phase--the formation of a volcano within the andesite plug--the ejecta of which mantles the slopes with andesitic tuff and breccia.

Along the east side of the study area, the alluvial fans and flood-plain deposits of Pleistocene age have been termed the Victor Formation by Olmsted and Davis (1961), after the type Victor Formation of Piper et al. (1939). The Victor Formation consists of an heterogeneous assemblage of clay, silt, sand and gravel, transported by shifting streams from the Sierra Nevada, and has a maximum thickness of 150 feet. The base of the Victor in most places is in conformable contact with the Laguna Formation. Toward the center of the Valley, it is at many places conformably overlain by basin and river deposits of Recent age. In general, the Victor Formation is not appreciably consolidated, although some of the beds have a high proportion of clay and silt which act as a binder. Hardpan layers, representing buried soil zones, occur at various depths, though most are within six feet of the surface.

The Red Bluff Formation is a poorly sorted gravel which has a distinctly reddish silty or sandy matrix and lies on an erosion surface cut on the Tehama Formation. This Pleistocene deposit is of no importance with regard to this report.

The sediments of Recent age include the river and flood-basin deposits. The river deposits consist predominantly of well-sorted sand, gravel, and silt along the channels, flood plains, and natural levees of the major streams. The basin deposits are largely silt and clay deposited in the flood basins during floods on the major streams. The sediments of Recent age range in thickness from zero to 100 feet.

Geologic Structure

Regional Features

The Sacramento Valley is a large structural basin filled with sedimentary rocks ranging in age from Early Cretaceous to Recent. The Valley trough is asymmetrical; the deepest part of the basin lies near the western margin of the Valley, west of the present axis and plunges to the south. The plunge of the Valley trough results in the southern part of the Valley--the Rio Vista Basin--containing the thicker and more complete geologic section.

The basement complex, beneath the Valley floor, is a continuation of the Sierra Nevada fault block that has been tilted toward the southwest. Geophysical evidence indicates that the basement lies some 20,000 feet below the surface along the western edge. Deep wells that have cored the basement complex in the Sacramento Valley indicate that the surface of the block slopes more steeply beneath the central part of the Valley than it does to the east.

The western part of the Valley is bounded by strike ridges underlain by Cretaceous and Lower Tertiary marine sedimentary rocks. Compressive forces deformed the

Coast Ranges sediments into tightly folded anticlines, synclines, and local thrust faults. Vaughan (1943) suggested that these same compressive forces caused the tilting of the rigid Sierra Nevada block by forcing its western part down below its position of isostatic equilibrium.

Sutter Buttes

The Sutter Buttes comprise the major structural and topographic feature in the study area, rising some 2,000 feet above the flat Valley floor. The Buttes are the surface expression of an intrusion of rhyolite porphyry, followed by andesite porphyry (Johnson, 1943) that forced its way upward from an unknown, but great depth, through at least a portion of the underlying "Basement Complex" platform, into and through some 7,500 feet of Cretaceous and Tertiary sediments. The rising laccolith greatly disturbed the sediments intruded and not only sharply tilted them away from the locus of intrusion, but produced an intricate series of radial and peripheral faults. Furthermore, radial and lateral anticlines and synclines were developed, some of them of sufficient amplitude to involve all of the exposed sediments.

After a period of quiescence and erosion, a series of violent explosions of steam and mud took place and a mile-wide central crater located just west of the middle of the great andesitic plug. Great angular masses of andesite and rhyolite, some of them measuring 30 feet or more in diameter, were thrown from this opening and were swept by mudflows down the slopes of the volcano to find a resting place about its periphery.

Erosive processes have brought the Sutter Buttes to their present form. The present-day Buttes are 10 miles in diameter and form an almost perfect circle. The Buttes can be divided into three concentric zones of rock types: the central core, the saddles and low areas surrounding the central core, and an outermost ring of tuff-breccia slopes.

The central core is a roughly circular area three to four miles in diameter, dominated by a cluster of sharp, steep-sided erosional remnants of a laccolith, with South Butte rising to a height of 2,117 feet.

The saddles, low hills, and ridges surrounding the central core are underlain by sedimentary rocks of Tertiary and Late Cretaceous age that were pushed up and fractured when the core was emplaced. This zone is approximately one mile in width and ranges in elevation from 200 to 500 feet above the valley floor.

The tuff-breccia slopes which form the outermost ring are two to three miles wide and have been dissected by erosion. The altitudes range from about 500 to 800 feet at the top of the slopes, and 50 to 100 feet at the foot of the slopes.

Dunnigan Hills Anticline

The Dunnigan Hills structure is an asymetrical anticline, steep on the east flank and gentle on the west flank, and is about 20 miles in length. The anticline plunges to the south, resulting in the subsequent burial of the deformed Tehama and Red Bluff Formations beneath younger valley alluvium along the southern portion. The time of folding is believed to have been during Late Pleistocene.

Faults

The only fault identified in this report is the Sutter Basin Fault (Figs. 5, 6 and 7). The location of this fault is based on electric log correlation and geophysical evidence. It is depicted as a vertical fault, striking N70°W, 11 miles in length, with the south block moving up approximately 500 feet in relation to the north block. The eastern extension of the fault is concealed by the "Markley Gorge," and to the west of the fault appears to die out as it is not discernable in wells further west. The age of the faulting appears to be Upper Eocene.

Around the Sutter Buttes numerous faults occur as the result of the igneous intrusives. The surface expressions of some of these faults have been mapped on Figure 4.

Published investigations of gas fields in the area reveal numerous faults to the south of the Buttes and along the west side of the Valley. Most of the faulting to the south of the Buttes is confined to the Forbes Formation. The few faults that extend above the Forbes (Weagant, 1964) are strike-slip faults trending to the north or northwest, and terminate at the base of the Capay Shale. Since the strike of the faults is approximately parallel to the direction of the ground water flow and the Capay Shale appears to act as a barrier to the upward migration of saline water, these faults have not been illustrated on Figure 5.

In general, the fault systems can be divided into three groups: (1) those that are confined to the Upper Cretaceous sediments only; (2) those that cut the Eocene and Cretaceous rock units; and (3) those that were formed by the Sutter Buttes intrusives during Upper Pliocene time.

Historical Geology

The first geologic event pertinent to the hydrogeology of the Sutter Basin was the deposition of the Upper Cretaceous sediments. According to Weagant (1964), in F-zone time (Forbes Formation), there was transgression of the sea and sediments were deposited by progressive onlap on the Lower Cretaceous shale. East of the central portion of the study area the Lower Cretaceous sediments are fully overlapped by the F-zone. The Forbes Formation was deposited in a moderately deep water environment too far from the shore to be affected by shore-line winnowing processes. These sediments consist of interbedded dark gray claystones and siltstones, and gray, fine-grained friable, lenticular sands. The eastern limit of the F-zone transgression is not known but members of the Forbes Formation crop out along the eastern side of the Sacramento Valley.

The rate of sedimentation was slightly greater than the rate of subsidence, so that the basin gradually shallowed and the E-zone Kione sands as well as some of the uppermost F-zone sands are near-shore sands associated with the shallowing.

The Kione sands were probably deposited in a series of deltas that lay at the mouth of the major drainages coming off of the Sierran land areas to the east. These deltaic sands were further distributed along the east side of the valley by action of along-shore currents and by normal shoreline processes.

Basinal shallowing was accompanied by uplift along the western basin margin with the regression of the sea to a position southwest of the Grimes gas field (Fig. 4). The basin then subsided rapidly, and the Sacramento Shale sea transgressed the area. The Sacramento shales were deposited in a moderately deep water basin.

Again the basin became shallow as the Winters Shales and Sands were deposited. The Starkey represents a very shallow sea environment with deposition of a series of regressive-transgressive beach or near-beach sands.

Following the deposition of the Upper Cretaceous sediments, probably in Late Paleocene time, the basin was uplifted, tilted southerly, and folded into a broad syncline with a north-south trending axis. The eastern margin of the sea was upwarped (Olmsted and Davis, 1961) and a land mass created east of the present position of the Sutter Buttes. The area then underwent extensive peneplanation.

The sea did not completely withdraw from the Sacramento Valley during Paleocene time, as attested by the deposition of the marine sediments of the Martinez Formation, in the southern part of the Valley. The Paleocene sea in which the Martinez Formation was deposited was confined to a restricted portion of the Delta area by barrier beaches (Safonov, 1962). Behind these beaches, lagoonal, swamp, and flood-plain deposits of sand and silt were laid down. The numerous beds of coal and the erratic character of the sediments as shown on electric logs attest to the predominantly nonmarine nature of the Martinez in this area. In late Paleocene time, the sea readvanced, continuing to do so into early Eocene Meganos time.

At the close of Meganos time, gradual subsidence allowed the Eocene sea to continue to spread over the entire Sacramento Valley area. The basin remained relatively quiet as the Capay Shale was deposited. The Capay Shale marks the last major sea transgression into the Sacramento Valley. Being widespread and conspicuous on electric-logs, it is an excellent marker bed. The Capay Shale reflects the post-Capay movement of the Valley, the southerly tilt, and the trough effect.

During Middle Eocene time the sea shallowed again and the deltaic deposits of the Ione-Domengine Formation of Stewart (1949) were laid down. To the east, the alluvial and lagoonal sediments of the Ione Formation of Allen (1929) were deposited. Lignite seams and severely weathered sediments of the Ione Formation attest to a warm, humid climate.

Following the Capay transgression a minor transgression of the sea in Upper Eocene time is reflected in the deposition of the Nortonville Shale member of the Kreyenhagen Formation. Then the sea began to withdraw from the Sacramento Valley.

Near the end of Eocene time the area was again uplifted, and eroded. The "Markley Gorge" of Davis (1953) was being carved and the entire study area was undergoing erosion. Almgren and Schlax (1957) believe that the "Markley Gorge" Fill was predominantly nonmarine deposits of Oligocene and possibly Miocene time.

Commencing in the Middle or Late Eocene and continuing sporadically into Miocene time, volcanic eruptions deposited rhyolitic, andesitic, and basaltic pyroclastic and flow rocks near the present crest of the Sierra Nevada (Piper et al., 1939). The streams eroded this material and redeposited it in the valley as water-laid tuff, tuffaceous sand and volcanic gravel. After a period of erosion and relative quiet, predominantly andesitic eruptions began during the Late Miocene in the northern Sierra Nevada and sent a flood of mudflow breccia and ash down the western slopes. Streams continually reworked these deposits and spread them over broad areas to the west.

The volcanic activity waned and died out and the latter part of the Pliocene epoch was marked by erosion in the Sierra Nevada and subaerial deposition (Laguna Formation) in the Sacramento Valley.

In the Middle or Late Pliocene time (Olmsted and Davis, 1961) an uplift of the present northern Coast Ranges inaugurated a period of erosion in the mountains and deposition of coarse detritus to the east. The Sacramento Valley trough began to assume approximately its present outline. Fluviatile deposition continued through the Pliocene and possibly into the early Pleistocene. The streams continually shifted across broad, low flood plains and deposited the Tehama Formation.

During Middle Pleistocene both the Coast Ranges and the Sierra Nevada appear to have been subjected to orogenic processes, and it is possible that this is the time that the Sutter Buttes were formed. The Coast Ranges were folded, faulted, and elevated and began to assume their present general outline and form. The Pliocene to Pleistocene (?) fluviatile sediments (Tehama Formation) and older rocks were involved in the folding and uplift. Dunnigan Hills anticline was formed at this time. During and after this mountain-building activity, erosion was vigorous, and much of the Tehama Formation was removed and redeposited in the center of the Valley or carried southward by the Sacramento River. Poorly sorted, gravelly material (Red Bluff Formation) eventually was deposited on the eroded surface of the Tehama.

The rejuvenated streams cut laterally and truncated the soft sediments of the Laguna Formation that had been deposited during the Late Pliocene. Most of the detritus was carried westward to be deposited near the axis of the Valley, and in this report is considered part of the Victor Formation.

The present cycle is one of continued erosion of the Coast Ranges, the Sierra Nevada and low hills, and deposition in the Valley.

WATER QUALITY

Connate Water

The term "connate water" has been used several times in this report. Connate water, as originally defined by A. C. Lane (1908) is "water that has remained since burial with the specific rocks in which it occurs, and that its chemical composition has remained unchanged." D. E. White (1965) has summed up the more recent ideas about connate water by saying (pg. 345):

> Much recent evidence indicates that (1) the original interstitial water of sediments normally undergoes diagenetic changes related to bacterial activity and decomposition of organic matter; (2) inorganic reactions between mineral phases and interstitial water occur during early and late diagenesis and also during metamorphism; (3) compaction always occurs, at least to some extent, in response to sediment load, so water must migrate either locally or extensively in directions of decreasing potential; (4) 'salt-sieving' mechanisms, only slightly understood until very recent years, account for changes in salinity of probably all deep waters of sedimentary basins; and (5) other mechanisms, even less well understood, account for changes in chemical composition of saline waters.
>
> Connate water, as here defined, generally is similar in age or somewhat younger, since last direct contact with the atmosphere, than the age of its associated rocks. Most connate waters are probably marine in origin and are associated with normal marine sediments, but some are suspected of being connate to marine and nonmarine evaporites. The dilute meteoric water 'born with' normal nonmarine sediments is probably never preserved in

> its original relationships but is normally displaced after burial by other dilute waters and eventually by any saline water (with higher density) that has access to the sediments.

In this report the water with a high chloride content is believed to have been derived from a marine source when the sediments were deposited in the open sea or in embayments with limited access to the sea. The latter case seems true for the sands of the Upper Cretaceous and Eocene deposits, because their chloride content is about half of that of normal sea water. These waters are termed "connate" under the definition of White (1965).

Basic Data

One hundred thirty-seven water quality analyses were obtained from the files of the California Department of Water Resources for use in this investigation. As many as space would allow are depicted with circle diagrams on Figure 6. Most of the analyses were determined during the 1964-67 period and consist of the standard analyses (i.e., only the major ions were determined). All of the chemical analyses are tabulated in Appendix A.

Approximately 400 electric-logs were used to correlate the formations and zones in the study area. These logs were also used as a guide to the quality of the ground water. The large differences in resistivity for potable and saline water are easily interpreted. Problems arise when one attempts to relate resistivity to degree of salinity. Besides the many assumptions that must be made, it is necessary to compute the resistivity of the formation from cores or drill cuttings, or have water quality samples from the formation in question. Lacking this, the electric-logs can be used only in a general way for determining water quality.

Variations of Water Quality

Vertical Variation

The entire study area is underlain at varying depths with saline water of marine origin. East of the Feather River, the base of the fresh water is at or near the base of the post-Eocene non-marine sediments. The fresh-water base slopes from near surface, at the areas of outcrop along the eastern margin of the Valley, to depths of 1,100 feet below the town of Verona and approximately 650 feet beneath Yuba City.

Throughout most of the Sutter Basin the base of the fresh water is at a depth of less than 500 feet and in the southern part of the Basin it rises to the surface. Along the western edge of the Sutter Basin the base of the fresh water again deepens and reaches a maximum depth of over 2,300 feet in T.10N., R.1E. A trough of fresh water trends to the northwest beneath Colusa Basin and also shallows to the northwest.

To the west of the trough the base of the fresh water again shallows and is at or near the base of the Tehama Formation along the western boundary of the Valley.

Around the Sutter Buttes the marine sands of the Ione-Domengine and the Kione Formations have been flushed with fresh (meteoric) water to depths of over 2,100 feet. Between the Buttes and the City of Colusa is another mound of saline water which is associated with the near-surface occurrence of Cretaceous beds.

If the base of the fresh water south of the Sutter Buttes were to coincide with the base of the nonmarine sediments, then there would be a gradual deepening of the base of the fresh water across the Sutter and Colusa Basins toward the trough of the Valley. Instead, the base of the fresh water shallows in the Sutter Basin and then deepens in the Colusa Basin.

Horizontal Variation

The river water that flows through the area is very good in quality. It is a calcium bicarbonate type with a total dissolved solid (TDS) content of between 50 and 150 parts per million (ppm). When the river water enters the ground water basin by influent seepage it is in a new environment and changes in quality to reach equilibrium with its new environment. It increases in total dissolved solids and changes to a magnesium bicarbonate type water. This is due to the large percentage of andesitic and basaltic debris that is present in the alluvial material.

In contrast to the magnesium bicarbonate type fresh water is the poor quality sodium chloride water that occurs in the Sutter Basin between Tisdale Weir and the town of Robbins (Fig. 6). The sodium chloride type water is unlike either the river water or ground water elsewhere in the area. The development of a pumping trough to the northwest along the Feather River has caused the saline water to move into this area and contaminate the ground water. This movement has been continuous over the years and has caused the farmers to abandon their water wells and resort to Feather River water for irrigation.

HYDROCHEMICAL PROCESS

Recharge Waters and Equilibrium

Recharge of the ground water basin is coming from three main sources: infiltration of rain water, river water, and excess irrigation. These three sources consist of water of high quality. One of the conclusions of this paper is that rising connate water is contaminating the ground water basin.

For saline water to move up and displace the fresh water in 2,000 feet of alluvial material requires a driving force or hydraulic head. The saline connate water was originally contained in the marine sediments of Upper Cretaceous and Eocene age. When the igneous intrusives of the Sutter Buttes forced their way up through the overlying sediments they dragged up the marine sediments and exposed them at the surface around the central zone of the Buttes. The marine sediments now stand some 250 to 400 feet above the surrounding flocr of the Valley. In time (some 1,200,000 years) runoff water of meteoric origin infiltrated the Ione-Domengine and Kione sands, both at outcrop and along faults and fractures, and displaced the saline water of marine origin.

Electric-logs run in wells around the southern half of the Buttes indicate that the fresh water has displaced the connate water to depths of over 2,000 feet. The displaced connate water in the Ione-Domengine Formation has many avenues of escape (Fig. 5) and has contributed saline water to the lower part of the nonmarine sediments in the ground water basin. The hydraulic gradient or head that developed in the Kione Formation, from the Buttes south to the Sutter Basin, has only one avenue of release and that is up the Sutter Basin Fault (Figs. 5, 6 and 7). Therefore it is proposed that the connate water in the Kione Formation moves south from the Sutter Buttes and up the fault, causing a mound of saline water to move to the surface. This movement of high chloride water continues to the present as fresh water infiltrates the Kione sands at the Sutter Buttes. It is possible that the connate water in the Ione-Domengine Formation is also contributing some saline water to the mound, but it appears that the major contributor is the Kione Formation.

There is not enough information available now to determine whether the Sutter Basin Fault zone is pervious and allows the connate water to move through it or that it acts as a barrier and forces the saline water to rise along the north side of the fault.

For a time this investigator thought that the Starkey Sands of Upper Cretaceous age was the main contributor of the saline water. But it now appears that the presence of the Starkey Sands in contact with the overlying nonmarine alluvium (Fig. 6) beneath the mound of saline water in the Sutter Basin has nothing to do with the saline phenomenon. It was hypothesized that the overburden on the confined portion of the Starkey would develop the required pore pressure to move the connate water up through the valley alluvium to the surface. However, a check of "closed in" pressures conducted in gas wells drilled into the Starkey Sands revealed that the pore pressure was approximately equal to the hydraulic load. This means that no abnormal pore pressure has been developed in the Starkey, and therefore there is no hydraulic head to move the saline water through the alluvium and up to the surface in the Sutter Basin.

Base Exchange

When ground water comes in contact with solid phase materials different from the ones it had been in contact with previously, chemical reactions may occur. This is particularly true when the water comes in contact with finely divided solids such as silt and clay that have an adsorptive capacity. One type of adsorption is termed "ion exchange" and is the replacement of adsorbed ions by ions in solution. The capacity for ion exchange is mostly a result of unsaturation of the chemical bonding in the crystal lattice of the solid having this capacity. In most cases there is an excess of negative bonds in certain areas of the crystal lattice, and positively charged ions are attracted to these areas. Most of the ion exchange reactions involve cations (calcium, magnesium, potassium, and sodium) and are therefore called base exchange.

After the ground water has been in contact with the solids a sufficient length of time, cations in solution and the adsorbed ions held by the exchange material constitute a system in chemical equilibrium. The degree and readiness for displacement of the equilibrium to the right or left is governed by the law of mass action, which means that if water or mineral holds some base in large excess, the exchange of that base for another proceeds more readily. The replacing power of the different metallic cations differ widely. Calcium possesses high replacing power; magnesium stands next, followed by potassium and then by sodium. Normally, calcium and magnesium ions from solution replace adsorbed sodium on the exchange material and the water is naturally softened. However, under certain conditions explained by the Le Chatelier's principle the system can be reversed and the ground water will undergo a hardening process. According to the principle of Le Chatelier any equilibrium system subjected to a stress tends to change so as to relieve the stress. For a system in chemical equilibrium, changing the concentration of one of the components constitutes a stress (Sienko and Plane, 1966). Thus, if we introduce a large supply of sodium ions into the ground water body that has reached chemical equilibrium a stress has been applied. Now the adsorbed calcium and magnesium ions will be replaced by the sodium ions in solution and the replacement will continue until the system is again in chemical equilibrium. This is exactly the procedure used in many domestic water softening systems. The water flows in contact with zeolites which act as an ion exchanger. Calcium ions are exchanged for sodium ions being held by the zeolite molecules. Once the exchanger has given up its supply of sodium ions it cannot soften water further. However, it can be regenerated by exposure to a concentrated solution of sodium chloride which reverses the reaction.

Piper et al. (1953) in their study of the contaminated ground water in the Long Beach-Santa Ana area of California found that the introduction of sea water or oil field brines high in sodium chloride resulted in the substitution of calcium (and locally some magnesium) for a large part of the sodium in the contaminating water. In other words, the strongly contaminated waters had been hardened by base exchange reactions, and the degree of hardening was greater than could be explained by the simple admixture of sea water and fresh water. They postulated that the influx of ocean water into the zones of native calcium bicarbonate type water released previously adsorbed calcium and magnesium by base exchange. This condition is also found in the Sutter Basin, where the rising connate water, high in sodium chloride, comes in contact with the calcium-magnesium bicarbonate type ground water of low total dissolved solids, and is changed to a calcium-magnesium chloride type with a high total dissolved solids. In both instances, we see a case of water being hardened by base exchange.

Source and Movement of Ions

Bicarbonate-Carbonate

There is a very limited occurrence of bicarbonate minerals in the Sutter Basin and the drainage areas of the Sacramento River and its tributaries. Based on the work of Bear (1964), this investigator concludes that the bicarbonate and carbonate anions in the ground water come mostly from the carbon dioxide contained in the soil, and in a small part from the precipitation that has been in contact with carbon dioxide in the atmosphere.

The following chemical equations indicate how these reactions might take place:

$$CO_2(\text{gas}) + H_2O = CO_2(\text{aqueous}) + H_2O$$
$$CO_2(\text{aqueous}) + H_2O = H_2CO_3$$
$$H_2CO_3 = H^+ + HCO_3$$
$$HCO_3^- = H^+ + CO_3^{--}$$

Of the 137 water analyses tabulated in Appendix A, 106 samples have the bicarbonate ion as the major anion. This bicarbonate type water is considered the normal condition for the ground water basin and is found on all sides of the mound of high chloride type water.

Sulfate

Feth, J. H., Robertson, C. E., and Polzer, W. L. (1964) propose that most of the sulfate ions in the runoff water of the Sierra Nevada come from water rising along fault zones. The author is aware of a source of sulfur in the upper Feather River drainage called Sulfur Point. The concentration of the sulfur compounds at Sulfur Point is so high that the stream is uninhabitable for fish within a mile below the Point.

The Bear River carries more sulfate ions than the other rivers flowing through the study area. Surface water samples contain as much as 0.56 equivalent parts per million (epm) with a TDS of 180 ppm. Water in well 13N/4E-21A1 is classified as a magnesium sulfate type and is the only well water that has sulfate as the major anion. Well 13N/4E-17J1, which is also near the Bear River (Fig. 6), has the second highest sulfate content among the ground water analyses used in this report.

Throughout the rest of the area the sulfate ions make up the minor constituent of the anion group. This is particularly true for the ground water with a high chloride content. A case in point is well 12N/2E-2J1 that has a TDS of 3525 ppm and a sulfate content of 2.0 ppm. Several other wells with high chloride water, in the same area, have no discernible amounts of sulfate in the water analyses.

Hem (1970) has proposed the following reaction for sulfate reduction:

$SO_4^{--} + CH_4$ (bacteria) $HS^- + H_2O + HCO_3^-$

This formula suggests that in the reduction of the sulfate the anaerobic bacteria is the most active agent. Methane gas is known to be present in the area. Bear (1964, p. 279) suggests that though the mechanism of sulfate reduction has still not been completely worked out, the activities of sulfate-reducing organisms are chiefly restricted to heavy clays or water logged soils. Such conditions are found in the Sutter Basin. One of the by-products of sulfate-reducing organisms is hydrogen sulfide with its characteristic odor. Bryan (1923) reported that much of the ground water in the eastern part of the Sutter Basin contained small quantities of hydrogen sulfide and that "many local people prefer the 'sulphur' water for drinking."

Chloride

A study of Figure 6 shows that there is a body of high chloride water in the central part of the Sutter Basin. Possible explanations for this are: (1) concentration of the chloride ion by evaporation of the ground water at or near the surface, (2) buried beds of sodium chloride salt, and (3) connate water rising from marine sediments. Byran (1923) noted that the conditions for residual evaporates existed in the basins of the Sacramento Valley but they were found only in small, isolated bodies. His reasons for the absence of extensive evaporates has already been cited. Drilling has not revealed any buried salt bodies such as exist in the Phoenix area of Arizona. Therefore, it appears most logical that the chloride ions are the result of marine connate water. In the past, the major stumbling block to this theory was that the high chloride occurs in nonmarine alluvial material with a thickness of approximately 2,000 feet.

Chloride ions are resistant to ion exchange, hence maintain their identity as ions after introduction into a ground water body. They are, therefore, ideal for use as tracers in ground water studies. Notice on Figure 6 the area between the Sutter Basin Fault and the Pumping trough to the north, west of the Feather River. The pumping for irrigation water has reversed the natural gradient of ground water and has resulted in the saline water slowly moving north and degrading the ground water. What is of interest to this thesis is that even though the degrading saline water has been diluted and subject to base exchange, the water still maintains a high percentage of chloride ions.

Sodium and Potassium

Feth et al. (1964) state that the igneous rock in the Sierra Nevada contained almost equal portions of sodium and potassium, however, once the ions have been taken into solution by the ground water, the potassium ions are subject to base exchange and rapidly disappear from the ground water, while the sodium ions persist and are carried by the rivers down to the valley ground water basin. This is confirmed in the water analyses in the study area. In both the surface water and the ground water, the sodium ions far outnumber the potassium ions. The two ions have been grouped together in the circle diagrams on Figure 6.

Throughout most of the area, sodium is the minor constituent in the cation group. As the water percolates through interstices of the alluvial material, normally the sodium ions are released to the ground water at the expense of the calcium and magnesium ions in solution. This process of base exchange is known as natural "softening" of the water. There is some evidence that this process is taking place, but in general it is masked by the infiltration of irrigation water diverted from the rivers.

Water analyses of the two deep wells (12N/2E-18 SW1/4 and 12N/2E-24L1, Appendix A) show that the deep waters contain 73.8 and 73.5 percent (of total anion reactance) sodium ions, respectively. South of the Sutter Basin Fault the deep connate water does not change chemically as it rises to the surface. Yet, as this same water moves Northward it becomes harder by changing from a sodium chloride type to a calcium-magnesium chloride type. As previously stated, this phenomenon was observed by Piper et al. (1953) in the Long Beach-Santa Ana area where fresh ground water was being contaminated with sea water. There, as in the Sutter Basin, the contaminated zone contains water which is higher in calcium and magnesium than can be explained by assuming a simple admixture of the saline water and fresh water involved. The best explanation is that previously adsorbed calcium and magnesium ions are being released by base exchange in the presence of the high sodium ion solution. That is to say, the water moving to the North is undergoing a base exchange, or hardening process. And on the other hand, the water moving Southwesterly from the Sutter Basin Fault is moving through soil that now has a deficiency of exchangeable calcium and magnesium ions and maintains its identity as a sodium chloride type water--the difference being that the saline water has been moving north only since the ground water trough was developed by irrigation pumping, whereas the ground water had been moving in a southerly direction for many thousands of years.

Calcium and Magnesium

The river water flowing through the area and recharging the ground water basin is a calcium-magnesium bicarbonate type with a TDS of between 50 and 150 ppm. Once it has infiltrated the basin, it changes to a magnesium-calcium type. The probable explanation for this is that the alluvium has a high content of ferromagnesium minerals due to the presence of andesitic volcanic debris. By the law of mass action and through base exchange, the magnesium ions are released to the ground water and the calcium ions are adsorbed by the soil particles.

Boron

The Feather River and its tributaries are free of boron although a trace is reported from time to time along the lower reaches. The ground water being recharged by the Feather River and its tributaries is also free of boron. Along the eastern edge of the Sacramento Valley, some of the water from wells contains boron that is believed to be coming from marine sediments that occur at shallow depths.

The streams and rivers draining the Coast Ranges generally have a high boron content. Cache Creek, in Capay Valley, has a boron content of up to 4 ppm. The ground water recharged by the western streams normally contains one to two parts per million boron.

Within the mound of saline water in the Sutter Basin the boron content ranges from 10.8 ppm at a depth of 1,500 feet to 1.5 ppm at a depth of 285 feet. As the rising connate water moves laterally away from the mound of saline water, the boron content gradually decreases until it is no longer detected in the analyses. The rapid decrease in boron over a vertical distance of some 1,200 feet is assumed to be largely the result of adsorption.

CONCLUSIONS

On the basis of the findings of this investigation, it is concluded that:

Subsurface Geology

The Kione Formation of Upper Cretaceous age is the chief contributor to the rising connate water in the Sutter Basin.

The Ione-Domengine Formation of Middle Eocene age also contributes saline water to the ground water basin but not in sufficient quantities to raise the base of the fresh water to the surface.

The "Starkey Sands" of Upper Cretaceous age are in direct contact with the overlying alluvial sediments in the southern portion of the Sutter Basin. This happenstance has nothing to do with the mound of saline water in the same area.

Hydraulic Continuity

The Sutter Basin Fault cuts the Upper Cretaceous marine sands and allows the saline water in the Kione Formation to rise along the fault into the post-Eocene alluvium.

Hydraulic Gradient

The head required to move the saline connate water from the underlying marine beds up through 2,000 feet of alluvium is supplied by the position of the Kione Formation which has been dragged up by the Sutter Buttes Intrusives and exposed at elevations between 250 and 400 feet above the Valley floor. The marine sands have been flushed with fresh water to depths of over 2,000 feet below sea level around the south side of the Buttes. The displaced saline water has moved south and up the Sutter Basin Fault and then through the overlying alluvial sediments to the surface.

Water Chemistry

The mound of saline water in the Sutter Basin is coming from connate water related to the marine sediments which underlie the entire area. The connate water is of a sodium chloride type that changes into a calcium-magnesium chloride type due to base exchange as the water moves into an area which previously contained calcium-magnesium bicarbonate type water.

APPENDIX A

ANALYSES OF GROUND WATER

		Chemical constituents			equivalents per million percent reactance value			parts per million		
Well Number	Depth ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
10N/1E-15H2	176	1.95 33.6	2.14 36.9	1.71 29.5	4.24 71.7	0.54 9.1	1.13 19.1	1.5	270	204
10N/2E-17J3	243	2.05 34.8	2.14 36.3	1.71 29.0	4.24 74.3	0.40 7.0	1.07 18.7	1.5	278	207
11N/1E-4R1	-	1.30 11.1	4.59 39.2	5.82 49.7	9.43 77.8	1.39 11.5	1.30 10.7	4.2	695	295
11N/1E-16P1	172	1.85 32.2	2.06 35.9	1.83 31.9	4.74 80.2	0.23 3.9	0.93 15.8	1.3	304	195
11N/2E-14F4	330	1.35 24.9	1.73 31.9	2.35 43.3	4.78 86.3	0.20 3.6	0.56 10.1	0.7	277	153
11N/2E-32G1	-	1.45 13.1	5.85 52.9	3.75 33.9	7.26 68.7	1.00 9.5	2.31 9.5	3.3	604	366
11N/3E-3N2	112	0.75 39.5	0.25 13.2	0.90 47.4	1.73 91.0	0.08 4.2	0.02 5.3	0.1	131	50
11N/3E-14N2	-	3.59 28.8	3.40 27.2	5.49 44.0	4.30 34.1	0.18 1.4	8.10 64.0	0.3	705	351
11N/3E-14R1	236	1.20 10.0	0.30 2.5	10.51 87.5	4.83 40.0	0.06 0.9	7.17 59.1	0.2	718	75
11N/3E-24D1	145	2.18 30.8	2.88 40.4	2.05 28.8	6.92 93.4	0.15 2.3	0.31 4.3	0.2	365	253
11N/3E-36L1	140	0.37 9.5	0.23 5.9	3.33 84.7	3.20 82.5	0.20 5.2	0.48 12.4	0.3	246	30
11N/4E-3P2	305	2.30 40.6	2.38 42.0	0.99 17.5	4.49 82.1	0.11 2.0	0.87 15.9	0.0	295	234

Well Number	Depth ft.	Chemical constituents	equivalents per million percent reactance value					parts per million		
		CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
11N/4E-9D1	-	1.40 42.2	1.32 39.7	0.60 18.1	2.60 76.3	0.50 14.7	0.31 9.0	0.1	184	138
11N/4E-14D2	204	0.83 26.1	0.99 31.1	1.36 42.8	2.16 77.7	0.08 2.9	0.54 19.4	0.2	152	91
11N/4E-19E2	-	1.35 31.4	1.41 32.8	1.54 35.8	3.00 69.3	0.31 7.2	1.02 23.5	0.1	262	138
12N/1W-21A1	405	1.50 32.7	2.30 50.3	0.78 17.0	4.20 97.5	0.00 0.0	0.11 2.5	0.0	214	189
12N/2E-2J1	100	30.37 28.2	35.30 33.4	39.90 37.8	4.10 4.0	0.05 0.0	99.45 96.0	0.6	5610	205
12N/2E-9B2	-	1.35 20.6	0.03 4.0	5.17 79.0	3.89 65.2	0.33 5.5	1.75 29.3	0.5	402	69
12N/2E-11N1	-	1.55 12.5	1.15 9.3	9.70 78.2	4.30 36.0	0.00 0.0	7.61 64.0	0.9	728	135
12N/2E-14B1	-	7.58 18.3	9.21 22.2	24.65 59.5	3.12 7.9	0.00 0.0	38.63 92.1	0.8	2790	841
12N/2E-16R1	-	2.25 21.5	0.72 6.9	7.46 71.6	7.13 70.0	0.35 3.5	2.68 26.5	0.6	577	148
12N/2E-18SW	1500	19.83 19.2	7.22 7.0	76.12 73.8	2.71 2.5	0.08 0.1	99.98 97.4	10.8	5870	166
12N/2E-23Q1	-	1.15 12.1	0.55 5.8	7.82 82.1	4.50 48.4	0.01 0.0	4.79 51.6	0.7	571	85

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value						parts per million		
		CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
12N/2E-24G1	446	0.70 7.6	0.72 7.9	7.61 84.5	4.00 47.4	0.35 4.1	4.09 48.5	0.1	670	-
12N/2E-24L1	1565	19.81 19.3	7.23 7.2	75.21 73.5	2.70 2.6	0.08 0.1	100.03 97.3	10.8	5940	-
12N/2E-24L2	146	19.81 36.5	9.29 17.1	25.23 46.4	3.47 8.1	0.02 0.0	39.48 91.9	1.1	2452	-
12N/2E-26A1	-	1.40 13.3	0.72 6.8	8.41 79.9	4.64 44.8	0.00 0.0	5.72 55.2	0.6	608	107
12N/2E-35SW	44	4.09 15.3	5.84 21.7	16.88 63.0	4.20 15.4	0.01 0.0	23.41 84.6	0.4	1628	-
12N/3E-13F1	285	0.85 20.3	0.47 11.2	2.87 68.5	2.91 69.8	0.02 0.5	1.24 29.7	0.2	266	66
12N/3E-16H2	-	2.15 19.0	4.45 39.3	4.73 41.7	5.28 47.1	2.21 19.7	3.71 32.2	0.0	620	330
12N/3E-23G1	120	6.47 36.6	4.72 26.7	6.49 36.7	2.82 15.9	0.23 1.3	14.72 82.8	0.4	1060	561
12N/3E-25A1	155	2.05 41.3	1.45 29.2	1.46 29.4	4.02 79.2	0.25 5.0	0.76 15.1	0.1	286	175
12N/25C2	97	3.79 50.1	2.20 29.1	1.58 20.9	4.13 54.9	0.75 10.0	2.65 35.2	0.1	435	252
12N/3E-26R1	-	2.99 42.2	1.64 23.1	2.46 34.7	3.52 48.6	0.17 2.4	3.55 49.0	0.1	423	234

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value						parts per million		
		CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
12N/3E-30H1	232	4.64 13.9	2.96 8.9	25.71 77.2	3.18 9.7	0.19 0.6	29.34 89.7	1.5	1970	380
12N/4E-4N2	89	1.45 36.2	1.75 43.6	0.81 20.22	2.72 68.3	0.19 4.8	1.07 26.9	0.0	257	160
12N/4E-6G1	82	2.50 26.2	4.30 45.0	2.76 28.8	6.20 69.0	2.17 24.1	0.62 6.9	0.2	491	340
12N/4E-7R1	100	0.95 32.3	1.35 45.9	0.64 21.8	2.63 92.9	0.02 0.7	0.18 6.4	0.0	181	115
12N/4E-32J1	-	4.39 42.8	4.19 40.8	1.68 16.4	4.25 41.6	2.08 20.4	3.89 38.1	0.0	682	427
13N/1W-15R2	-	1.80 33.3	1.23 22.8	2.37 43.9	4.03 75.9	0.21 4.0	1.07 20.5	0.5	287	153
13N/1W-36Q2	36	1.75 38.6	1.15 24.9	1.72 36.5	3.31 74.3	0.15 3.4	0.99 22.3	0.3	276	145
13N/1E-22J1	-	2.84 52.4	1.48 27.3	1.10 20.3	3.71 69.6	0.17 3.2	1.44 27.0	0.1	327	216
13N/1E-36Q1	-	1.75 37.9	1.15 24.9	1.72 37.2	3.31 74.4	0.15 3.4	0.99 22.2	0.3	276	145
13N/2E-23B1	72	17.41 28.0	21.18 38.7	20.87 33.3	3.54 5.6	0.00 0.0	59.80 94.4	0.4	5970	2080
13N/3E-2C4	190	3.64 36.8	3.67 37.1	2.58 26.1	5.94 61.2	0.98 10.1	2.79 28.7	0.2	486	-

		Chemical constituents equivalents per million percent reactance value						parts per million		
Well Number	Depth ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
13N/3E-14G1	-	5.56 21.5	14.18 54.9	6.08 23.6	2.98 11.2	3.39 12.9	20.01 75.9	0.1	1994	987
13N/3E-15B1	95	6.99 31.5	9.01 40.6	6.20 27.9	2.75 12.5	0.06 0.3	19.18 87.2	0.1	1400	800
13N/3E-15C2	90	8.53 37.6	10.85 44.0	5.29 21.4	4.18 16.8	0.06 0.2	20.68 83.0	0.1	1580	970
13N/3E-23C1	105	13.40 41.9	13.00 40.6	5.60 17.5	5.92 18.7	0.10 0.3	25.60 80.8	0.2	1884	1320
13N/3E-23H1	-	5.10 30.7	7.70 46.4	3.80 22.9	3.43 20.7	0.46 2.8	12.65 76.5	0.1	900	640
13N/3E-24D1	-	7.80 26.2	11.80 39.6	10.21 34.2	1.46 4.8	0.23 0.8	28.50 94.4	0.5	2140	980
13N/4E-3D1	130	1.30 22.2	3.30 56.3	1.26 21.5	3.93 68.0	0.19 3.3	1.66 28.7	0.0	320	230
13N/4E-17J1	200	2.45 39.5	2.75 44.3	1.01 16.3	3.33 56.7	2.00 34.1	0.54 9.2	0.02	387	260
13N/4E-21A1	-	3.59 36.3	5.26 53.2	1.04 10.6	4.31 42.9	5.45 54.3	0.28 2.8	0.0	565	445
13N/4E-27M1	196	0.70 29.4	1.02 42.9	0.66 27.7	1.92 84.2	0.02 0.9	0.34 14.9	0.0	163	86
13N/4E-32N1	84	0.95 23.4	1.43 35.2	1.68 41.4	2.41 83.1	0.12 4.1	0.37 12.8	0.0	200	119

		Chemical constituents			equivalents per million					
	Depth				percent reactance value			parts per million		
Well Number	ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
13N/4E-33J2	154	1.95 35.7	2.55 46.6	0.97 17.7	4.56 85.6	0.09 1.7	0.68 12.8	0.0	312	-
14N/1W-2D1	-	2.84 31.8	2.47 27.6	3.63 40.6	3.67 40.6	1.64 18.2	3.72 41.2	0.2	493	268
14N/1W-12A1	-	1.05 17.6	0.09 1.5	4.83 80.9	4.41 74.7	0.02 0.3	1.47 24.9	0.5	319	57
14N/1E-1A1	-	3.24 45.5	2.63 36.9	1.25 17.6	6.05 88.1	0.37 5.4	0.45 6.6	0.0	344	294
14N/1E-24N1	125	1.60 34.0	1.73 36.0	1.42 30.0	3.99 86.0	0.441 10.0	0.19 4.0	0.1	248	166
14N/2E-13L1	79	1.20 29.6	1.81 44.7	1.04 25.7	3.90 96.3	0.06 1.5	0.09 2.2	0.0	205	150
14N/2E-17E1	330	1.25 25.9	1.25 25.9	2.32 48.2	3.93 83.6	0.33 7.0	0.48 9.4	0.1	298	196
14N/2E-30R1	188	1.90 27.8	1.58 23.1	3.37 49.1	5.22 77.5	0.21 3.1	1.30 19.4	0.1	386	174
14N/3E-4E5	160	2.20 26.0	4.12 48.7	2.14 25.3	5.61 71.0	1.44 18.2	0.85 10.8	0.0	455	316
14N/3E-5A3	106	4.39 34.5	5.18 40.8	3.14 24.7	8.30 66.4	2.08 16.6	2.12 17.0	0.1	670	481
14N/3E-5D2	150	1.50 29.8	2.10 41.7	1.44 28.6	4.54 91.9	0.17 3.4	0.23 4.7	0.0	266	180

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value						parts per million		
		CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
14N/3E-6A1	100	2.50	3.29	1.80	6.54	0.58	0.20	0.0	363	180
		32.9	43.4	27.7	89.3	7.9	2.7			
14N/3E-7H1	105	1.90	4.18	1.86	6.06	0.58	1.18	0.0	401	304
		23.9	52.6	23.4	77.5	7.4	15.1			
14N/3E-9K1	230	2.99	3.57	2.45	3.65	0.19	4.96	0.1	628	328
		33.2	39.6	27.2	41.5	2.2	56.3			
14N/3E-13D1	650	1.00	0.68	0.98	2.01	0.00	0.62	0.2	198	84
		37.6	25.6	36.8	76.4	0.0	23.6			
14N/3E-14E2	90	1.10	1.07	0.29	2.25	0.10	0.10	0.0	118	104
		44.7	43.5	11.8	91.8	4.1	4.1			
14N/3E-16B2	99	4.09	7.15	2.74	4.18	1.60	8.23	0.1	895	564
		29.3	51.1	19.6	29.8	11.4	58.7			
14N/3E-18A2	125	2.69	3.29	1.69	6.39	0.58	0.90	0.1	396	301
		35.1	42.9	22.0	81.2	7.4	11.4			
14N/3E-20H3	105	2.59	3.19	1.74	5.35	0.58	1.35	0.1	385	289
		34.4	42.3	23.1	73.5	8.0	18.5			
14N/3E-23M2	83	0.90	1.16	0.36	2.41	0.02	0.04	0.0	385	289
		37.2	47.9	14.9	97.6	0.8	1.6			
14N/3E-24M1	-	1.75	2.06	1.30	3.56	0.69	0.71	0.1	280	191
		34.3	40.3	25.4	71.8	13.9	14.3			
14N/3E-24P1	-	1.15	0.53	1.08	1.95	0.00	0.73	0.2	184	84
		41.7	19.2	39.1	72.8	0.0	27.2			

		Chemical constituents			equivalents per million percent reactance value			parts per million		
Well Number	Depth ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
14N/3E-25D3	85	1.10 41.4	0.90 33.8	0.66 24.8	2.11 79.6	0.06 2.3	0.48 18.1	0.0	159	102
14N/3E-26D4	110	0.77 32.9	0.05 2.1	1.52 65.0	1.61 95.3	0.05 3.0	0.03 1.8	0.2	136	11
14N/3E-27K1	180	2.89 24.8	3.91 33.6	4.84 41.6	5.60 49.1	0.31 2.7	5.50 48.2	0.2	665	340
14N/3E-28E1	-	1.25 22.2	2.46 43.6	1.93 34.2	3.52 62.4	0.24 4.3	1.88 33.3	0.2	286	185
14N/3E-29Q1	-	5.12 26.9	6.52 34.2	7.40 38.9	2.92 15.6	0.10 0.5	15.67 83.8	0.4	1000	581
14N/3E-31B1	63	1.30 20.5	2.86 45.2	2.17 34.3	5.51 88.9	0.21 3.4	0.48 7.7	0.0	317	208
14N/3E-32F1	-	5.63 26.4	7.08 33.2	8.60 40.4	3.42 16.1	0.05 0.2	17.76 83.7	0.3	1135	635
14N/3E-33A1	-	3.99 30.3	6.04 45.9	3.13 23.8	2.60 19.7	0.05 0.4	10.54 79.9	0.1	682	501
14N/3E-33C1	-	3.04 21.0	7.76 53.7	3.64 25.2	3.06 21.0	0.13 0.9	11.37 78.1	0.2	806	540
14N/3E-34F1	84	3.49 28.1	4.31 34.7	4.63 37.3	4.96 40.5	0.00 0.0	7.28 59.5	0.1	750	390
14N/3E-34J1	-	1.80 18.9	5.80 60.8	1.94 20.3	3.62 38.3	1.29 13.6	4.55 48.1	0.1	481	380

		Chemical constituents			equivalents per million					
					percent reactance value			parts per million		
Well Number	Depth ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
14N/4E-6H1	112	1.00 44.4	0.58 25.8	0.67 29.8	1.86 81.6	0.07 3.1	0.35 15.4	0.0	116	79
14N/4E-7M1	83	2.25 35.3	2.87 45.0	1.26 19.7	3.51 56.3	2.19 35.1	0.54 8.7	0.0	528	395
14N/4E-9J1	100	1.64 33.3	2.06 41.8	1.23 25.0	3.54 73.1	0.15 3.1	1.15 23.8	0.0	242	165
14N/4E-22H1	400	0.70 31.3	0.64 28.6	0.90 40.2	1.52 70.4	0.02 0.9	0.62 28.7	0.0	191	67
14N/4E-27N1	510	0.80 36.0	0.50 22.5	0.92 41.4	1.92 86.9	0.06 2.7	0.23 10.4	0.0 0.0	148	65
15N/1E-16R1	-	1.90 27.5	3.78 54.7	1.23 17.8	5.84 85.8	0.35 5.1	0.62 9.1	0.1	355	283
15N/1E-35H1	108	2.20 35.1	2.96 47.2	1.11 17.7	5.22 85.6	0.20 3.3	0.28 4.6	0.0	225	-
15N/1E-35R1	-	3.84 47.4	3.53 43.6	0.73 9.0	5.28 66.1	0.62 7.8	2.09 26.2	0.0	466	370
15N/2E-1R1	49	2.10 36.5	2.55 44.3	1.01 17.5	4.69 88.2	0.46 8.7	0.17 3.2	0.0	310	231
15N/2E-22D1	306	1.05 36.0	0.99 33.9	0.83 28.4	2.54 89.4	0.10 3.5	0.10 7.0	0.0	184	100
15N/2E-26D2	-	3.24 40.9	2.79 35.2	1.90 24.0	5.23 74.2	0.44 6.2	1.38 19.6	0.1	447	304

Well Number	Depth ft.	Chemical constituents			equivalents per million percent reactance value			parts per million		
		CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
15N/3E-4C2	147	3.04 34.2	4.52 50.9	1.32 14.9	5.72 69.3	1.77 21.5	0.76 9.2	0.1	558	379
15N/3E-9C2	200	2.20 34.9	2.28 36.2	1.82 28.9	5.52 88.0	0.44 7.0	0.31 4.9	0.1	350	224
15N/3E-11H4	60	0.94 39.2	1.13 47.1	0.33 13.7	2.17 90.0	0.11 4.6	0.13 5.4	0.0	127	103
15N/3E-13F1	350	1.80 50.9	0.92 26.0	0.82 23.1	2.68 77.5	0.50 14.5	0.28 8.0	0.0	239	136
15N/3E-13J2	300	1.10 44.2	0.54 21.7	0.85 34.1	1.90 74.2	0.01 0.4	0.65 25.4	0.0	201	82
15N/3E-14N1	350	0.70 24.4	0.72 25.1	1.45 50.5	2.34 81.3	0.00 0.0	0.54 18.8	0.3	182	71
15N/3E-15C1	170	1.15 28.3	0.65 16.0	2.27 55.8	3.59 87.4	0.01 0.2	0.51 12.4	0.3	257	90
15N/3E-15E2	188	1.64 24.4	1.92 28.6	3.15 46.9	4.96 76.0	0.27 4.1	1.30 19.9	0.4	329	178
15N/3E-15H4	133	3.49 41.8	3.95 47.3	0.91 10.9	6.65 81.4	0.20 2.5	1.32 16.1	0.0	483	373
15N/3E-15J2	160	0.55 9.1	4.35 71.7	1.17 19.3	3.99 75.9	0.71 13.5	0.56 10.7	0.0	354	245
15N/3E-15Q1	-	0.70 16.8	0.86 20.6	2.61 62.6	3.61 84.6	0.04 0.9	0.62 14.5	0.3	262	-

Well Number	Depth ft.	Chemical constituents CA	MG	NA+K	equivalents per million percent reactance value HCO3+CO3	SO4	CL	parts per million B.	TDS	TH
15N/3E-19M1	75	0.94 30.2	1.39 44.7	0.78 25.1	2.79 92.1	0.09 3.0	0.15 5.0	0.1	150	117
15N/3E-21C1	185	1.30 23.6	2.86 51.9	1.35 24.5	4.47 81.1	0.25 4.5	0.79 14.3	0.0	328	208
15N/3E-22N1	115	3.49 34.4	4.75 46.8	1.90 18.6	7.42 74.6	0.75 7.5	1.78 18.0	0.0	529	412
15N/3E-23C1	118	0.75 46.3	0.65 40.1	0.22 13.6	1.41 92.2	0.05 3.3	0.07 4.6	0.0	99	70
15N/3E-23D1	125	2.25 38.3	3.30 51.5	0.60 10.2	5.19 90.1	0.29 5.0	0.28 4.9	0.0	325	264
15N/3E-24F1	130	2.84 42.8	2.59 39.0	1.21 18.2	4.71 69.4	0.58 8.5	1.50 22.1	0.1	334	261
15N/3E-26C1	163	1.35 30.0	1.71 38.0	1.44 32.0	4.03 90.2	0.10 2.2	0.34 7.6	0.0	262	153
15N/3E-26M1	250	1.45 32.6	1.23 27.6	1.77 39.8	3.97 89.4	0.10 2.3	0.37 8.3	0.2	241	134
15N/3E-27C1	80	3.89 32.2	6.02 49.8	2.17 18.0	8.85 77.2	0.92 8.0	1.69 14.8	0.2	557	496
15N/3E-27L1	150	2.15 31.6	3.05 51.3	1.59 17.0	4.93 86.1	0.33 6.3	1.41 7.6	0.0	370	260
15N/3E-29G1	90	3.09 34.3	4.27 47.4	1.65 18.3	7.20 85.7	0.75 8.9	0.45 5.4	0.0	488	367

Well Number	Depth ft.	Chemical constituents			equivalents per million percent reactance value			parts per million		
		CA	MG	NA+K	HC03+C03	S04	CL	B.	TDS	TH
15N/3E-29G2	110	2.84 31.6	4.61 51.3	1.53 17.0	7.35 86.1	0.54 6.3	0.65 7.6	0.0	487	373
15N/3E-30D1	65	2.64 37.9	3.44 49.4	0.89 12.8	6.10 94.0	0.23 3.5	0.16 2.5	0.0	384	304
15N/3E-34N2	80	3.80 22.9	10.38 62.5	2.43 14.6	7.02 42.8	2.02 12.3	7.36 44.9	0.1	831	709
15N/4E-8D1	333	1.87 43.8	1.82 42.6	0.58 13.6	3.04 73.3	0.90 21.7	0.21 5.1	0.1	220	184
15N/4E-16P1	450	1.15 41.8	1.07 39.0	0.53 19.2	2.21 81.6	0.42 15.5	0.08 2.9	0.0	184	111
15N/4E-20J2	271	1.60 36.9	2.14 49.3	0.60 13.8	3.13 73.0	0.98 22.8	0.18 4.2	0.0	271	187
15N/4E-29H1	145	1.35 36.2	1.75 46.9	0.63 16.9	2.96 80.2	0.54 14.6	0.19 5.2	0.0	187	155
15N/4E-31A1	157	1.05 39.5	1.07 40.2	0.54 20.3	2.32 89.9	0.02 0.8	0.24 9.3	0.0	172	105
16N/1W-29J1	-	1.30 31.3	1.48 35.7	1.37 33.0	3.82 94.1	0.00 0.0	0.24 5.9	0.1	199	139
16N/3E-14G1	63	4.34 46.7	4.22 45.4	0.73 7.9	6.78 76.9	1.19 13.5	0.85 9.6	0.0	472	428
16N/3E-16B1	46	0.84 46.9	0.80 44.7	0.15 8.4	1.49 87.1	0.12 7.0	0.10 5.9	0.0	90	82

		Chemical constituents equivalents per million percent reactance value						parts per million		
Well Number	Depth ft.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
16N/3E-23B1	160	1.13	1.08	0.61	2.38	0.10	0.15	0.0	160	110
		40.1	38.3	21.6	90.5	3.8	5.7			
16N/3E-26Q1	416	1.40	0.80	0.84	2.40	0.17	0.37	0.1	218	110
		46.1	26.3	27.6	81.6	5.8	12.6			
16N/3E-31C1	72	1.32	2.04	0.92	3.92	0.16	0.15	0.0	318	168
		30.8	47.7	21.5	92.7	3.8	3.5			
16N/3E-36E1	85	2.16	2.84	0.83	5.04	0.02	0.39	0.0	280	250
		37.1	48.7	14.2	92.5	0.4	7.2			

LITERATURE CITED

Almgren, A. A., and Schlax, W. N., 1957, Post-Eocene age of "Markley Gorge" fill, Sacramento Valley, California: Am. Assoc. Petroleum Geologists Bull., vol. 41, p. 326-330.

Allen, V. T., 1929, The Ione formation of California: Calif. Univ., Dept. Geol. Sci., Bull. 18, p. 347-448.

Anderson, C. A., and Russell, R. D., 1939, Tertiary formations of northern Sacramento Valley and southwestern edge of Cascade Range: Calif. Jour. Mines and Geology, vol. 35, p. 255-274.

Bear, F. E., 1964, Chemistry of the soil, 2nd ed., Am. Chem. Soc. Monograph Series, Reinhold Publishing Corp., New York.

Bryan, Kirk, 1923, Geology and ground-water resources of Sacramento Valley, California: U. S. Geol. Survey Water-Supply Paper 495, 285 p.

California State Water Resources Board, 1952, Sutter-Yuba Counties Investigation: Calif. State Water Res. Brd., Bull. 6, 174 p.

Clark, B. L., 1918, Meganos group a newly recognized division in the Eocene of California: Geol. Soc. of America, Bull. 29, p. 281-296.

________, 1926, The Domengine horizon, middle Eocene of California: Univ. Calif. Pubs., Dept. Geol. Bull., vol. 16, no. 5, p. 99-106.

Clark, B. L., and Woodford, A. O., 1927, The geology and paleontology of the type section of the Meganos formation (lower middle Eocene) of California: Calif. Univ., Dept. Geol. Sci., Bull. 17, p. 63-142.

Crook, T. H., and Kirby, J. M., 1935, Capay formation (abs.): Geol. Soc. of America Proc., 1934, p. 334-335.

Davis, D. M., 1953, Markley Gorge, Sacramento County, California (abs.): Am. Assoc. Petroleum Geologists, Bull. vol. 37, p. 186.

Davis, G. H., and Olmsted, F. H., 1952, Geologic features and ground water storage capacity of the Sutter-Yuba area, California: Calif. State Water Res. Brd., Bull. 6, app. B, p. 89-104.

Dickerson, R. E., 1914, The Martinez and Tejon Eocene and associated formations of the Santa Ana Mountains (Calif.): Ac. Sc. Proc. 4, p. 113-128.

Feth, J. H., Roberson, C. E., and Polzer, W. L., 1964, Source of mineral constituents in water from granitic rocks, Sierra Nevada, California and Nevada: U. S. Geol. Survey Water-Supply Paper 1535, 70 p.

Goudkoff, P. P., 1945, Stratigraphic relations of Upper Cretaceous in Great Valley: Am. Assoc. Petroleum Geologists Bull., vol. 29, p. 956-1008.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U. S. Geol. Survey Water-Supply Paper 1473, 2nd edition, 269 p.

Johnson, H. R., 1943, Marysville Buttes (Sutter Buttes) gas field: Calif. Div. Mines Bull. 118, p. 610-615.

Kirby, J. M., 1943, Upper Cretaceous stratigraphy of the west side of Sacramento Valley, south of Willows, Glenn County, California: Am. Assoc. Petroleum Geologists Bull., vol. 27, p. 279-305.

Laiming, Boris, 1943, Eocene foraminiferal correlations in California: Calif. Div. Mines Bull. 118, p. 193-198.

Lane, A. C., 1908, Mine waters and their field assay: Geol. Soc. of America, Bull. 19, p. 501-512.

Lindgren, Waldemar, 1911, The Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, 226 p.

Matthes, F. E., 1930, Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, 137 p.

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and ground water storage capacity of the Sacramento Valley, California: U. S. Geol. Survey Water-Supply Paper 1497, 241 p.

Piper, A. M., Gale, H. S., Thomas, H. E., and Robinson, T. W., 1939, Geology and ground water hydrology of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 789, 230 p.

Piper, A. M., Garrett, A. A., and others, 1953, Native and contaminated waters in the Long Beach-Santa Ana area, California: U. S. Geol. Survey Water-Supply Paper 1136, 320 p.

Rofé, Rafael, 1962, Dunnigan Hills gas field, California: Calif. Div. Mines and Geology Bull. 181, p. 119-131.

Sacramento Petroleum Association, 1962, Main Prairie gas field, California: Calif. Div. Mines and Geology Bull. 181, p. 132-139.

Safonov, Anatole, 1962, The challenge of the Sacramento Valley, California: Calif. Div. Mines and Geology Bull. 181, p. 77-97.

Sienko, M. J., and Plane, R. A., 1966, Chemistry: principles and properties: McGraw-Hill Book Co., New York.

Stewart, Ralph, 1949, Lower Tertiary stratigraphy of Mount Diablo, Marysville Buttes, and west border of lower Central Valley of California: U. S. Geol. Survey Oil and Gas Investigations, Prelim. Chart 34.

Vaughan, F. W., 1943, Geophysical studies in California: Calif. Div. Mines Bull. 118, p. 67-70.

Weagant, F. E., 1964, Grimes gas field: Selected Gas Fields by the San Joaquin Geological Society, p. 36-46.

Weaver, C. E., Beck, Stanley, Bramlette, S. C., Clark, B. L., Dibblee, T. W., Jr., Durham, Wyatt, Ferguson, G. C., Forrest, L. C., Grant, U. S. IV, Hill, Mason, Keeley, F. R., Kleinpell, R. M., Kleinpell, W. D., Marks, J., Putnam, W. C., Schenck, H. G., Taliaferro, M. L., Thorup, R. R., Watson, Elizabeth, and White, R. T., 1944, Correlation of the marine Cenozoic formations of western North America: Geol. Soc. America Bull., vol. 55, p. 569-598.

Weddle, J. R., 1968, Tisdale Gas Field, Calif. Div. Oil and Gas, Summary of Operations, vol. 54, no. 2, p. 29-34, pl. 3.

White, D. E., 1965, Saline waters of sedimentary rocks, in Fluids in subsurface environments, Addison Young and John E. Galley (eds.): Am. Assoc. Petroleum Geologists Memoir 4, p. 342-366.

Wilcox, L. V., 1948, Salt-balance conditions of Reclamation District no. 1500 in Sutter Basin for the year ending December 31, 1946: Mimeographed report for the U. S. Dept. of Agriculture.

Williams, Howel, 1929, Geology of the Marysville Buttes, California: Calif. Univ., Dept. Geol. Sci., Bull. 18, p. 103-220.

Wolfe, J. E., 1958, Notes on the occurrence of poor quality water in the Sutter-Yuba area: Calif. Dept. Water Resources, Office Report, 15 p.

LEGEND

NON-MARINE ROCK UNITS

RECENT

Qr River deposits

Sand, gravel, silt, and minor amounts of clay along channels, flood plains, and natural levees of major streams. Highly permeable.

Qb Flood-basin deposits

Largely silt and clay deposited in flood basins during flood stages of major streams. Generally of low permeability.

PLEISTOCENE-RECENT

Qf Alluvial-fan deposits

Heterogeneous fluviatile sediments ranging from clay and silt to coarse sand and gravel. Permeability extremely variable from place to place.

PLEISTOCENE

Qrb Red Bluff Formation

Poorly sorted gravel having reddish silty or sandy matrix. Locally may contain small bodies of perched

Qv Victor Formation

Lenticular silt, sand, gravel, and clay deposited by streams draining the Sierra Nevada. At most places moderately permeable throughout.

UPPER PLIOCENE-PLEISTOCENE

QTt Tehama Formation

Silt, sand, gravel, and clay, locally cemented, derived from Coast Ranges. Permeability variable, generally less than that of overlying alluvial-fan deposits. One of most important sources of ground water in the valley. In the southern part of the Sutter Basin contains saline water at all depths.

SUTTER BUTTES VOLCANICS

QTvt Vent Tuff

QTat Andesite Tuff-breccia

QTap Andesite Porphyry

QTrp Rhyolite Porphyry

Tuff-breccia, andesitic, of mudflow type. Poorly permeable, but supplies small amounts of water to wells near Sutter Buttes. Intrusive rhyolite and andesite, and vent tuff. Generally not water bearing, except in fractures.

MARINE ROCK UNITS

LOWER-UPPER EOCENE

Ec Ei En

En — Nortonville Shale (upper Eocene)
Clastic marine sedimentary rock consisting mainly of siltstone and shale with siltstone lenses, generally of low permeability. Contains connate or dilute connate saline water.

Ei — Domengine Formation - Ione Sand (middle Eocene)
White, quartzose, medium-grained, friable sandstone probably of deltaic origin. Source area the Sierra Nevada. Around the Sutter Buttes the connate water has been flushed with meteoric water to a depth of several thousand feet. Elsewhere the sand contains connate saline water.

Ec — Capay Shale (lower Eocene)
Marine, gray-green, glauconitic claystone and shale containing abundant foraminifera. Virtually impermeable, contains connate saline water.

UPPER CRETACEOUS

Kuk Kione Formation

Marine deltaic, white to yellow, friable, medium-grained, quartzose sandstone very similar lithologically to the Ione Sand. Derived from the Sierra Nevada. Around the east and south sides of the Sutter Buttes the sand is flushed with meteoric water to a depth of serveral thousand feet. Elsewhere the sand contains connate saline water.

Kuf Forbes Formation

Marine, gray and brownish clay shale varying to sandy, silty mudstone containing lenticular, fine-grained sandstone interbeds. Virtually impermeable, contains connate saline water everywhere beneath the study area.

GEOLOGY OF SUTTER BUTTES AREA AFTER H.R. JOHNSON (1943); DUNNIGAN HILLS GEOLOGY AFTER UNPUBLISHED MAPS OF CALIF. DEPT. OF WATER RESOURCES; BALANCE OF AREA BASED ON INTERPRETATIONS OF SOIL MAPS PUBLISHED BY U.S. DEPT. OF AGRICULTURE.

FIGURE 4

SURFICIAL GEOLOGY OF THE SUTTER BASIN AREA, SACRAMENTO VALLEY, CALIFORNIA

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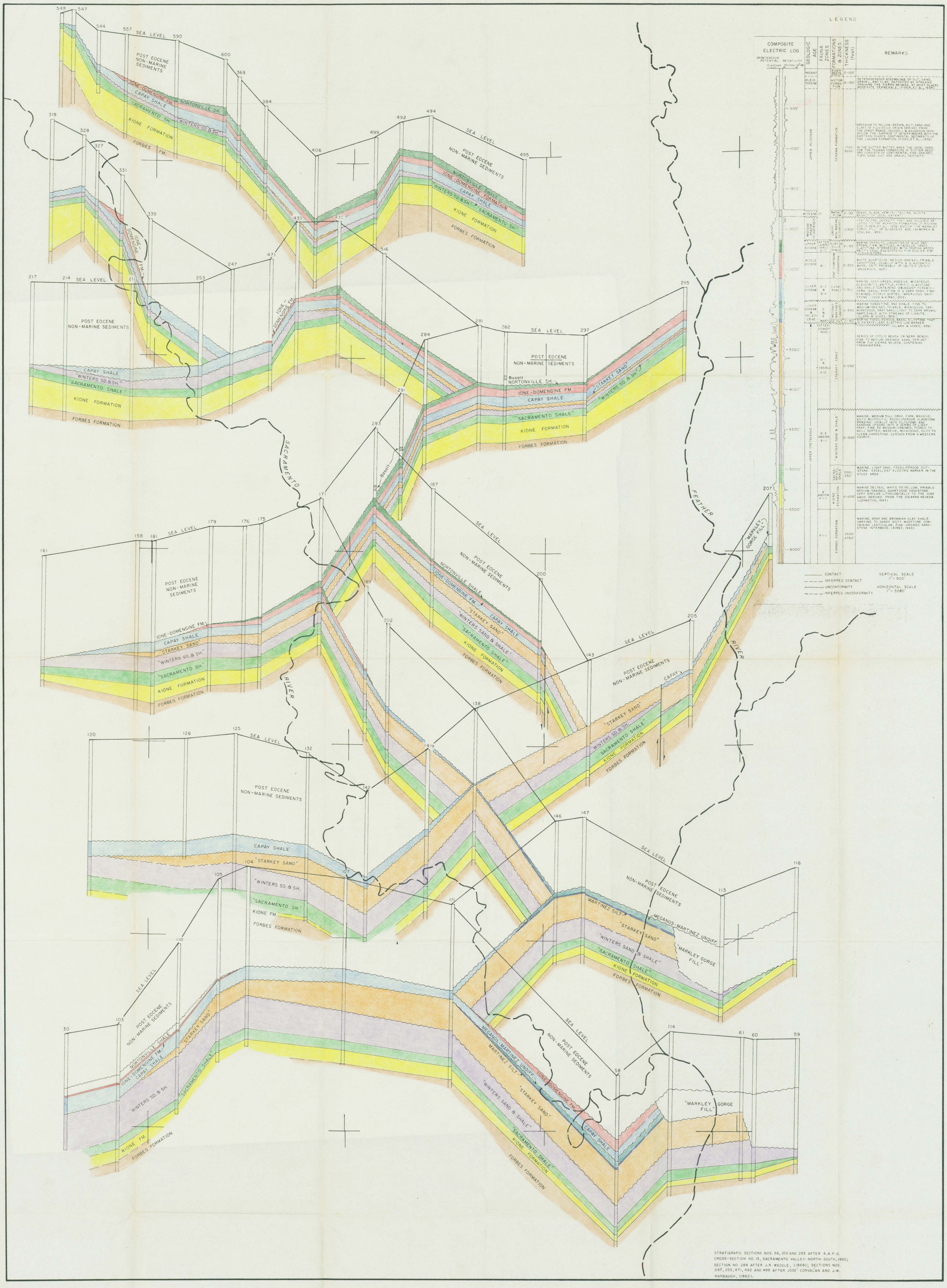

GEOLOGIC AGE	FAUNA ZONES	FORMATIONS & ZONES	THICKNESS (feet)	REMARKS
RECENT		RIVER-BASIN DEPOSITS	0-100'	
PLEISTOCENE		VICTOR FORMATION	0-150'	HETEROGENEOUS ASSEMBLAGE OF SILT, SAND, GRAVEL, AND CLAY, DEPOSITED BY STREAMS DRAINING THE SIERRA NEVADA. AT MOST PLACES MODERATE PERMEABLE. (PIPER, ET AL., 1939)
UPPER PLIOCENE		TEHAMA FORMATION	1700-3000'	GREENISH TO YELLOW-BROWN, SILT, SAND AND CLAYS OF FLUVIATILE ORIGIN DERIVED FROM THE COAST RANGE. (RUSSELL & ANDERSON, 1939) BELOW THE SURFACE IT INTERFINGERS WITH THE EASTERN-SOURCE CONTINENTAL SEDIMENTS OF THE LAGUNA FORMATION. (PIPER, ET AL., 1939) IN THE SUTTER BUTTES AREA THE LOCAL NAME FOR THE TEHAMA FORMATION IS "SUTTER BEDS" AND CONSISTS OF CONTINENTAL FINE-GRAINED, TUFF, SAND, SILT AND GRAVEL DEPOSITS.
MIOCENE(?)		BASALT FLOW	0-150'	DENSE, BLACK, HEMICRYSTALLINE AUGITE BASALT OF LOCAL EXTENT.
MIOCENE AND/OR OLIGOCENE(?)		UNDIFF. NON-MARINE SEDIMENTS	±300'	CONTINENTAL DEPOSITS THAT ARE POSSIBLY RELATED TO THE MEHRTEN FORMATION OF MIOCENE AGE (PIPER, ET AL., 1939) AND/OR THE "MARKLEY GORGE FILL" OF OLIGOCENE AGE (ALMGREN & SCHLAX, 1956)
UPPER EOCENE	(AFTER LAIMING 1940) A-2	NORTONVILLE SHALE	0-150'	MARINE DEPOSITS CONSISTING OF BLUE AND BROWN, FIRM, MOTTLED, MICACEOUS, SANDY CLAYSTONE INTERBEDDED WITH GRAYISH GREEN GRITTY SAND, AND CONTAINS FISH SCALES AND FORAMINIFERA
MIDDLE EOCENE	B-1	IONE DOMENGINE FORMATION	0-200'	WHITE QUARTZOSE, MEDIUM-GRAINED, FRIABLE SANDSTONE, USUALLY WITH A GLAUCONITIC BASAL GRIT, PROBABLY OF DELTAIC ORIGIN (ANDERSON, 1905)
LOWER EOCENE	B-2 & B-4	CAPAY SHALE	0-500'	MARINE, GRAY-GREEN, MASSIVE, MICACEOUS, GLAUCONITIC, BRITTLE, PYRITIC, CLAYSTONE AND SHALE CONTAINING ABUNDANT FORAMINIFERA. BASAL PORTION IS A DARK GRAY, FINE-GRAINED, POORLY SORTED, IMPERVIOUS GRITSTONE. (COOK & KIRBY, 1935)
LOWER EOCENE & PALEOCENE	D & E	MEGANOS MARTINEZ (UNDIFF)	0-200'	MARINE SANDSTONE AND SHALE. FINE TO MEDIUM-GRAINED, FRIABLE, MICACEOUS, CARBONACEOUS, GRAY SAND; LIGHT TO DARK BROWN, HARD SHALE WITH STREAKS OF LIGNITE. (CLARK & VOKES, 1936)
		"MARTINEZ SILT"	0-40'	MARINE FOSSILIFEROUS, BASAL SILTSTONE THAT IS AN EXCELLENT ELECTRIC LOG MARKER. (CLARK & VOKES, 1936)
UPPER CRETACEOUS	(AFTER GOUKOFF 1945) D-1 & POSSIBLE D-2	"STARKEY SAND"	0-1250'	SERIES OF CYCLIC BEACH OR NEAR BEACH, FINE TO MEDIUM-GRAINED SAND, DERIVED FROM THE SIERRA NEVADA, CONTAINING FORAMINIFERA.
	D-2 AND/OR E-1	"WINTERS SAND & SHALE"	0-1500'	MARINE, MEDIUM DULL GRAY, FIRM, MASSIVE, SILTY, MUSCOVITIC, FOSSILIFEROUS CLAYSTONE GRADING LOCALLY INTO SILTSTONE AND SANDING UPWARD INTO A SERIES OF LIGHT GRAY, FINE TO MEDIUM-GRAINED, POORLY TO WELL SORTED, MASSIVE, MICACEOUS, SILTY TO CLEAN SANDSTONE. DERIVED FROM A WESTERN SOURCE.
		"SACRAMENTO SHALE"	200-350'	MARINE, LIGHT GRAY, FOSSILIFEROUS SILTSTONE. EXCELLENT ELECTRIC MARKER IN THE STUDY AREA.
	E AND/OR F'-1	KIONE FORMATION	0-1000'	MARINE DELTAIC, WHITE TO YELLOW, FRIABLE MEDIUM-GRAINED, QUARTZOSE SANDSTONE VERY SIMILAR LITHOLOGICALLY TO THE IONE SAND. DERIVED FROM THE SIEARRA NEVADA. (JOHNSTON, 1943)
	F'-1	FORBES FORMATION	2500-4750'	MARINE, GRAY AND BROWNISH CLAY SHALE VARYING TO SANDY SILTY MUDSTONE CONTAINING LENTICULAR, FINE-GRAINED SANDSTONE INTERBEDS. (KIRBY, 1943)

CONTACT
INFERRED CONTACT
UNCONFORMITY
INFERRED UNCONFORMITY

VERTICAL SCALE
1" = 500'

HORIZONTAL SCALE
1" = 5280'

STRATIGRAPIC SECTIONS NOS. 58, 200 AND 293 AFTER A.A.P.G. CROSS-SECTION NO. 13, SACRAMENTO VALLEY-NORTH-SOUTH, 1960; SECTION NO. 284 AFTER J.R. WEDDLE, (1968); SECTIONS NOS. 247, 253, 471, 492 AND 499 AFTER JOSE' CORVALAN AND J.W. HARBAUGH, (1962).

FIGURE 5

PANEL DIAGRAM SHOWING THE STRATIGRAPHY OF THE SUTTER BASIN AREA, SACRAMENTO VALLEY, CALIFORNIA

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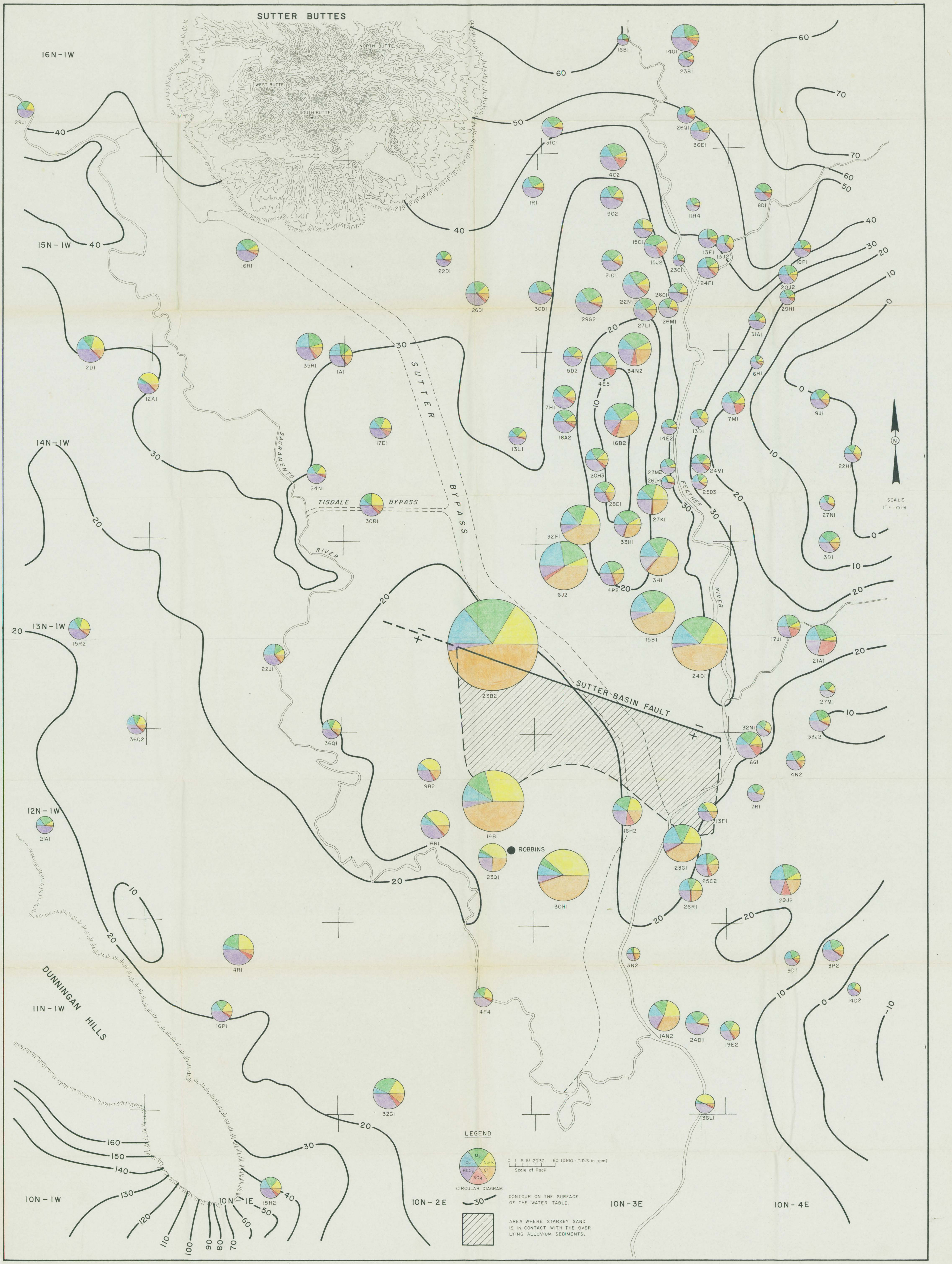

FIGURE 6 WATER QUALITY AND CONTOUR ELEVATION OF WATER IN WELLS, SPRING 1966 (SEA LEVEL DATUM) SUTTER BASIN AREA, SACRAMENTO VALLEY, CALIFORNIA

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SEE FIGURE 5 FOR EXPLANATION
SEE FIGURE 4 FOR LOCATION

FIGURE 7

GEOLOGIC SECTION A-A', SUTTER BASIN, SACRAMENTO VALLEY, CALIFORNIA

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