LIST OF ILLUSTRATIONS

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 rect-angular system for the subdivision of public land. For

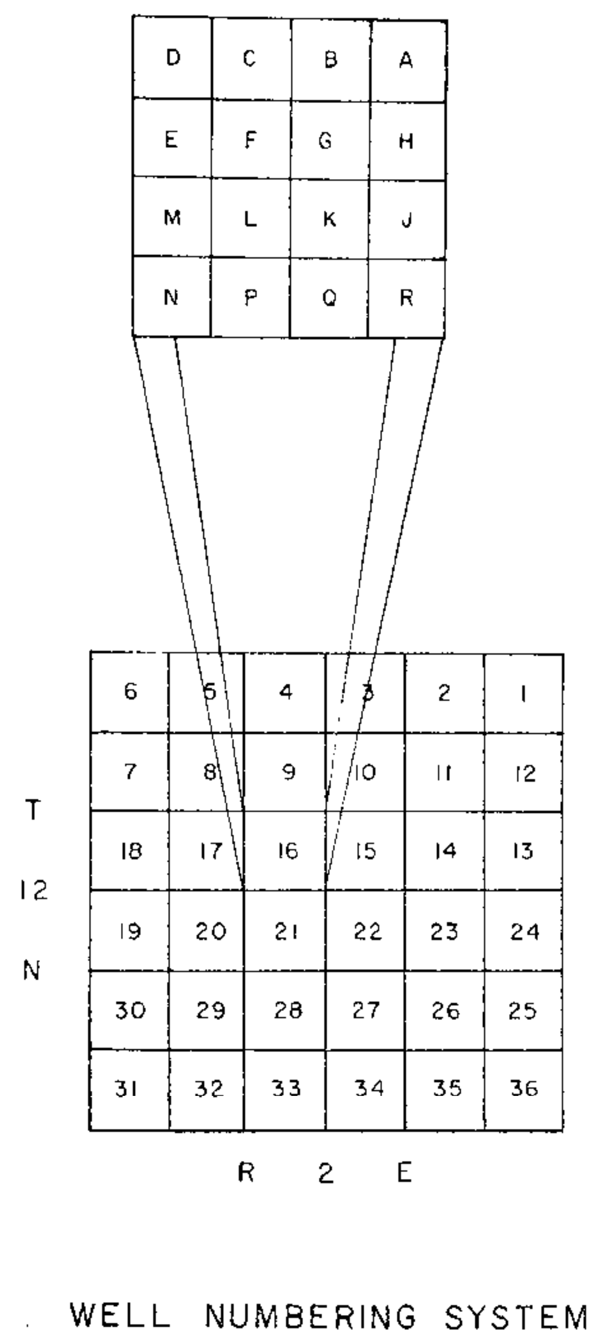

FIGURE 2 DIAGRAM SHOWING WELL NUMBERING SYSTEM

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.

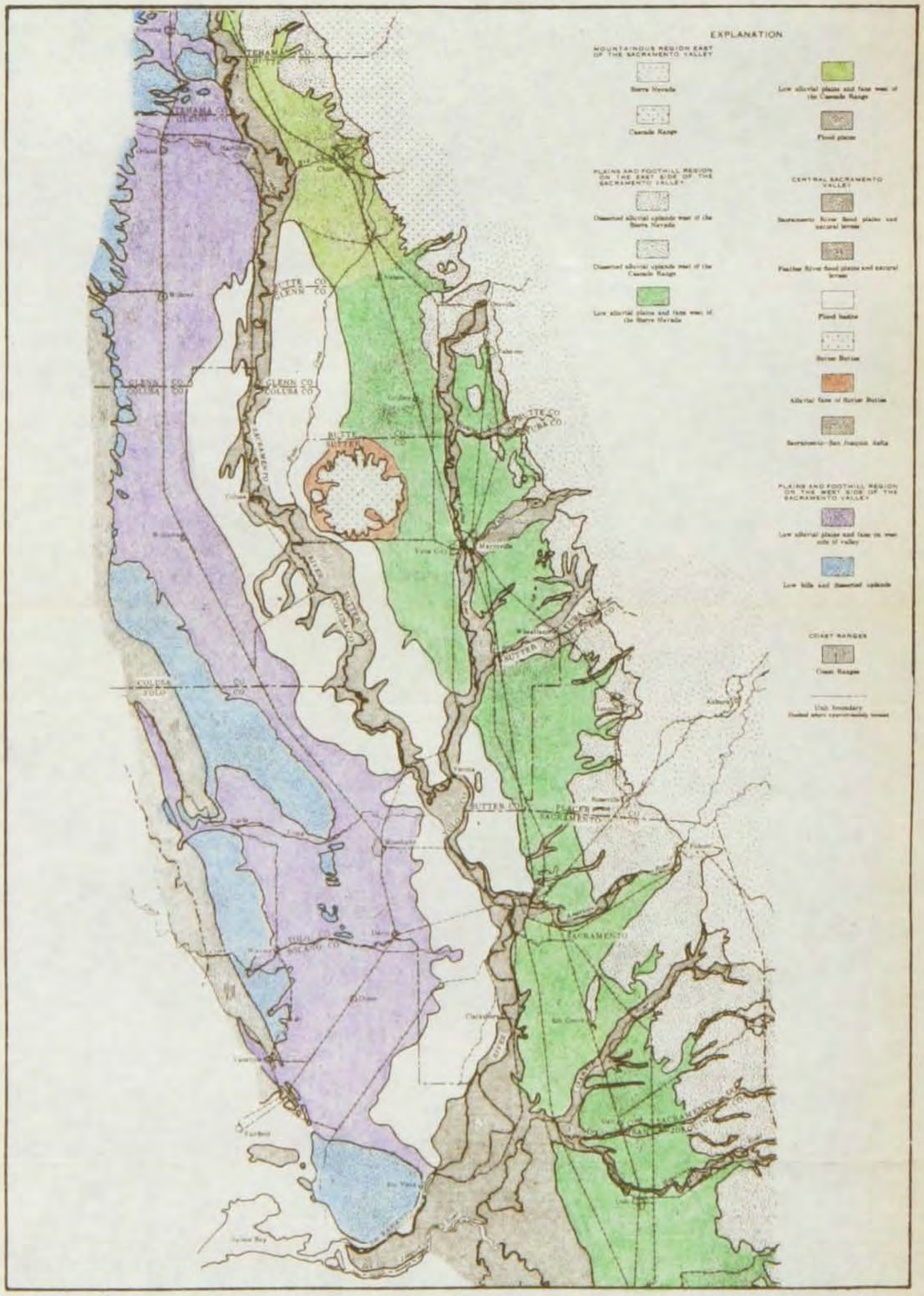

FIGURE 3

MAP OF THE SACRAMENTO VALLEY, CALIFORNIA, SHOWING GEOMORPHIC UNITS

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 sub-surface 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).

<u>Quaternary-Recent Units</u>

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:

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

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

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value: CA	MG	NA+K	HCO3+CO3	SO4	CL	parts per million: 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 CA	MG	NA+K	equivalents per million percent reactance value HCO3+CO3	SO4	CL	parts per million 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 CA	MG	NA+K	equivalents per million / percent reactance value HCO3+CO3	SO4	CL	parts per million 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	-

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value: CA	MG	NA+K	HCO3+CO3	SO4	CL	parts per million: 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

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

Well Number	Depth ft.	Chemical constituents equivalents per million percent reactance value CA	MG	NA+K	HCO3+CO3	SO4	CL	parts per million 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

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
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.	CA	MG	NA+K	HCO3+CO3	SO4	CL	B.	TDS	TH
		Chemical constituents equivalents per million percent reactance value						parts per million		
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	HCO3+CO3	SO4	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

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
16N/3E-23B1	160	1.13 40.1	1.08 38.3	0.61 21.6	2.38 90.5	0.10 3.8	0.15 5.7	0.0	160	110
16N/3E-26Q1	416	1.40 46.1	0.80 26.3	0.84 27.6	2.40 81.6	0.17 5.8	0.37 12.6	0.1	218	110
16N/3E-31C1	72	1.32 30.8	2.04 47.7	0.92 21.5	3.92 92.7	0.16 3.8	0.15 3.5	0.0	318	168
16N/3E-36E1	85	2.16 37.1	2.84 48.7	0.83 14.2	5.04 92.5	0.02 0.4	0.39 7.2	0.0	280	250

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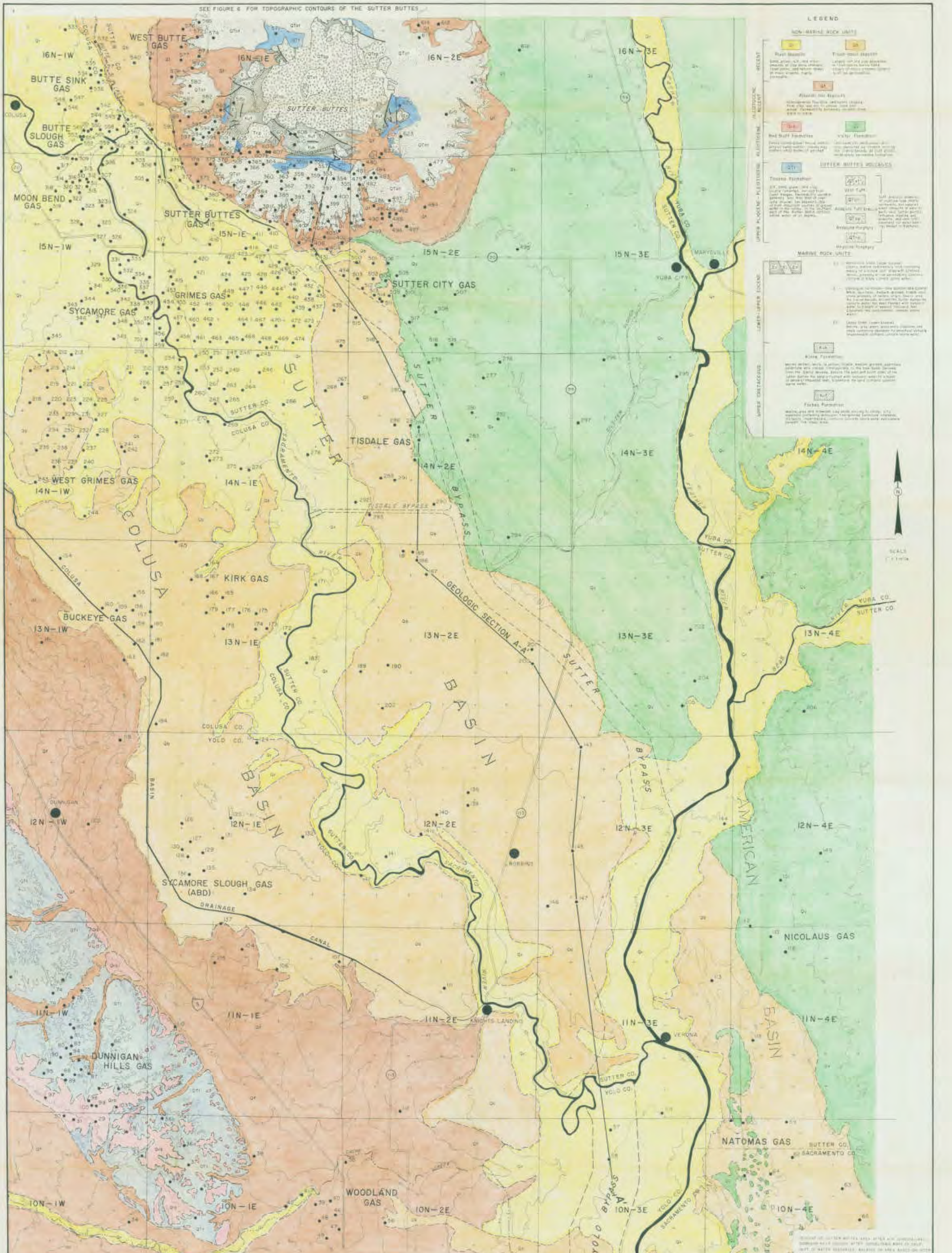

FIGURE 4

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

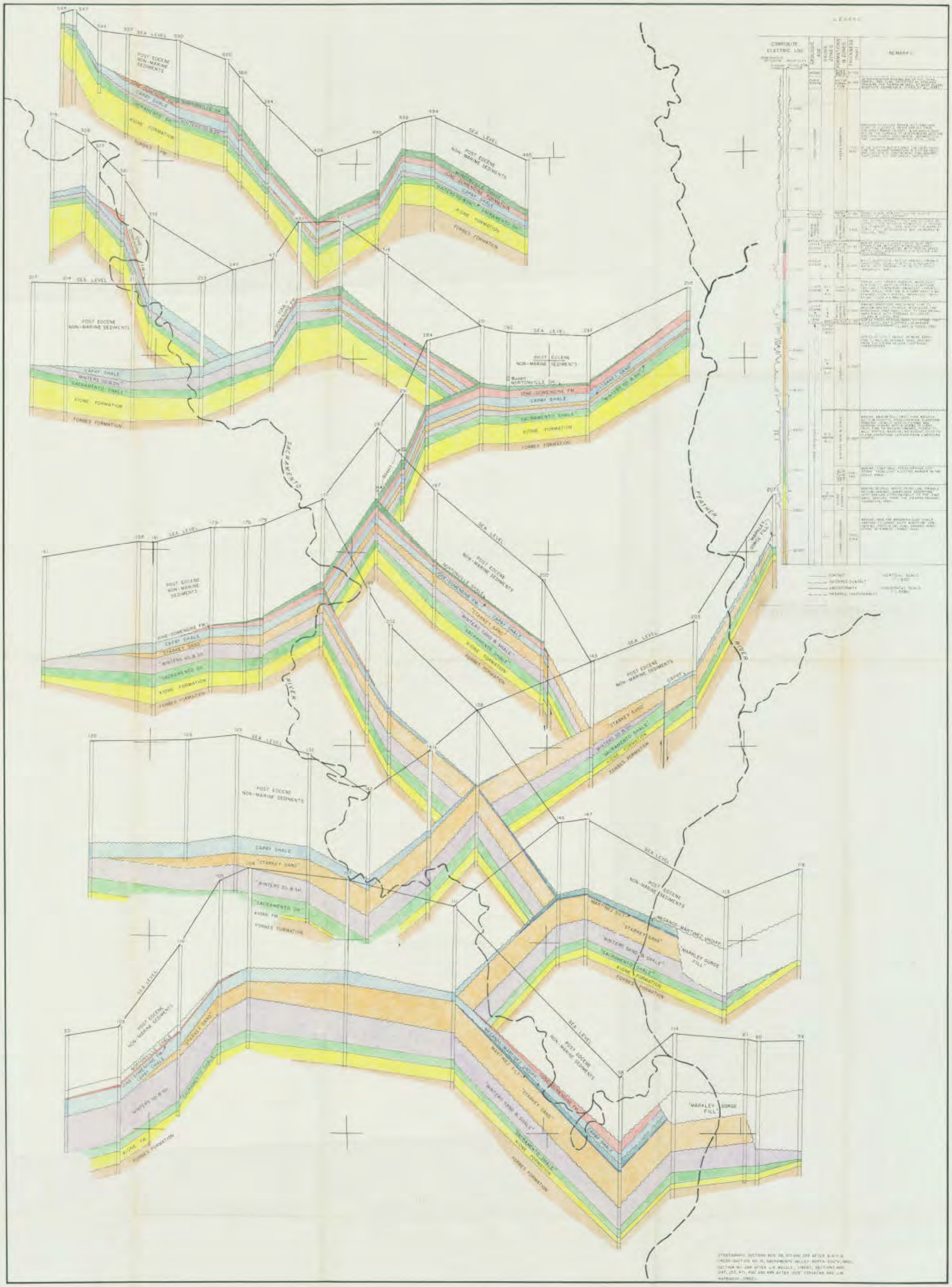

FIGURE 5

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

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

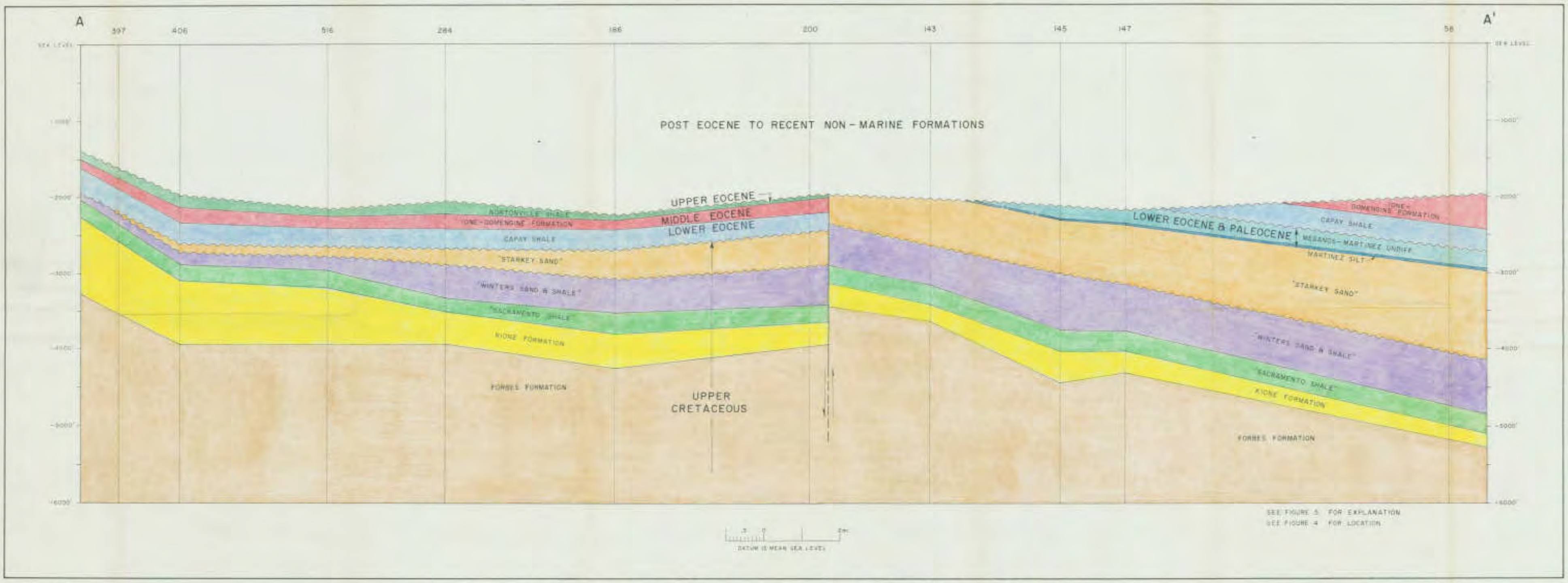

FIGURE 7

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

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GEOCHEMISTRY OF GROUND WATER IN THE SACRAMENTO VALLEY, CALIFORNIA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1401–B

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By LAURENCE C. HULL

CENTRAL VALLEY OF CALIFORNIA RASA PROJECT

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	*By*	*To obtain*
acres	0.004047	km^2 (square kilometers)
acre-ft (acre-feet)	0.001233	hm^3 (cubic hectometers)
ft (feet)	0.3048	m (meters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

Degrees Fahrenheit are converted to degrees Celsius by using the formula: °C=(°F-32)/1.8

Additional abbreviations:

µg/L	(micrograms per liter)
mm	(millimeters)
mg/L	(milligrams per liter)
(mg/L)/yr	(milligrams per liter per year)

National Geodetic Vertical Datum of 1929 (NGVD of 1929). A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is sometimes referred to as sea level in this report.

GEOCHEMISTRY OF GROUND WATER IN THE SACRAMENTO VALLEY, CALIFORNIA

By LAURENCE C. HULL

ABSTRACT

A geochemical investigation was done to evaluate temporal changes in water quality and to determine the processes that control water chemistry in shallow ground water of the Sacramento Valley, California. A total of 671 chemical analyses from 651 wells were used to study the processes controlling water chemistry. Temporal variations in dissolved-solids and nitrate concentrations were studied in 140 and 62 wells, respectively, having multiple observations with time.

The Sacramento Valley can be divided into six hydrochemical facies having distinctive chemical compositions. Waters from the Tuscan volcanic rocks and Victor Plain facies, along the eastern margin, have lower concentrations of dissolved solids and higher concentrations of silica than the waters from other areas of the Sacramento Valley. Ground waters in the basin hydrochemical facies (Butte Basin and Sutter Basin) along the valley axis are higher in iron, manganese, arsenic, and potassium. West side facies, the north alluvial fans and south alluvial fans, are low in silica. The south alluvial fans facies is higher in dissolved solids and has very high boron concentrations.

Significant increases have occurred in dissolved-solids and nitrate concentrations since the mid-1950's. Dissolved solids increased in five of the six hydrochemical facies, with rates ranging from 0.95 milligrams per liter per year in the Tuscan volcanic rocks facies to 4.75 milligrams per liter per year in the south alluvial fans facies. Nitrate-nitrogen did not significantly increase in the Tuscan volcanic rocks, Butte Basin, or Sutter Basin hydrochemical facies. Rates of increase of 0.036, 0.036, and 0.099 milligrams per liter per year occurred in the Victor Plain, south alluvial fans, and north alluvial fans, respectively.

Two processes control over 50 percent of the spatial variation in ground-water chemistry. Thirty-six percent of the variation in the data is explained by the effects of recharge water chemistry on the chemistry of ground water. Low dissolved solids and high silica from east-side recharge produces fairly uniform conditions in east-side ground waters. Recharge from the northwest is intermediate in dissolved solids and silica. Southwest recharge is high in dissolved solids, boron, and fluoride. High boron concentrations in the ground water originate in thermal springs in the Coast Ranges. A second important process consists of reactions occurring in the fine-grained sediments of the flood basin in the central part of the Sacramento Valley. Reducing conditions here produce higher concentrations of manganese, iron, and arsenic. Nitrate concentrations are low, probably reflecting denitrification reactions.

Precipitation and dissolution of aluminosilicates appear to control the relation between silica and aluminum in parts of the valley. Silica and aluminum in ground waters of the Sutter Basin hydrochemical facies show parallel behavior and have a ratio of 3 to 1. In the Tuscan volcanic rocks facies silica and aluminum are inversely related and are controlled by the solubility of halloysite. The clay minerals halloysite and illite were identified in the sediments. The clay mineral predicted to be the most stable in equilibrium with valley ground water is montmorillonite. Halloysite represents an intermediate step in the weathering of primary minerals to more stable secondary phases.

INTRODUCTION

GEOGRAPHY

The Sacramento Valley comprises the northern third of the Central Valley of California in the north-central part of the State (fig. 1). It is a sedimentary basin bounded by mountains to the east (Sierra Nevada), northeast (Cascade Range), and west (Coast Ranges). To the south, the valley merges with the delta of the Sacramento and San Joaquin Rivers. The area lies between 38°30′ and 40°15′ N. latitude, and 121°15′ and 122°30′ W. longitude. The valley covers about 4,400 square miles, is 150 miles in length from Red Bluff to the delta, and ranges in width from about 8 miles at Red Bluff to about 50 miles near the southern end. The topography consists of generally flat plains, with low dissected hills near the margins. The elevation of the valley at the southern end is near sea level, increasing northward and reaching 300 feet above sea level near Red Bluff. The relatively flat topography of the valley is interrupted near the center, where a volcanic neck of late Tertiary age, Sutter Buttes, rises 2,100 feet above the valley floor.

The Sacramento River enters the valley from the north and flows along the entire length of the valley before entering the delta region to the south. The Feather River is the only other principal stream that flows through the valley. The Sacramento and Feather Rivers are fed by tributaries draining the surrounding mountain areas. From the Sierra Nevada come the American, Bear, Yuba, and Feather Rivers. The Cascade Range is drained primarily by Big Chico, Butte, Mill, and Deer Creeks in the area adjacent to the Sacramento Valley. The streams entering the valley from the west rise in the Coast Ranges and are much smaller than the streams from the east. Thomes, Stony, Cache, and Putah Creeks are the only sizable streams entering

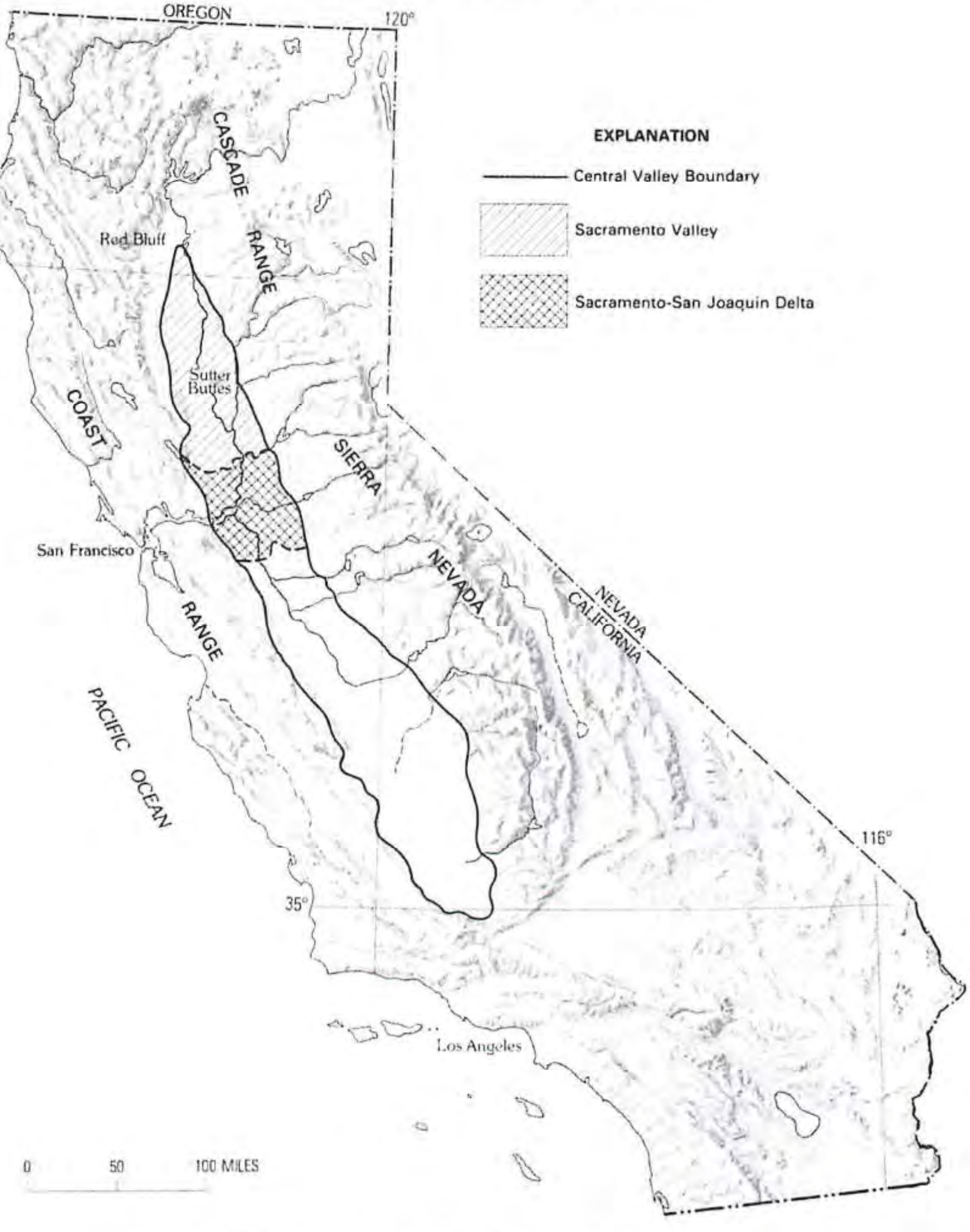

FIGURE 1.—Location map showing Sacramento Valley of California.

the west side of the valley. (See pl. 1*B* for stream locations.)

Little precipitation falls in the valley during the summer growing season, and irrigation is necessary to support extensive agricultural development. Early irrigated farming began in the mid-1800's as the gold miners moving to California created a demand for foodstuffs. Development of irrigation was slow, however, until the drought of 1864 stimulated the construction of new irrigation projects. During both world wars, heavy demand for agricultural products spurred periods of rapid development. Ground water has always lagged behind surface water as a source of irrigation water, amounting to only about 10 percent of the total use in the late 1910's. Since the late 1950's, however, the use of ground water has been increasing, and in 1970, it accounted for about 40 percent of all irrigation water used in the Sacramento Valley.

PURPOSE AND SCOPE

The U.S. Geological Survey began a series of hydrologic investigations—the regional aquifer systems analysis (RASA) program—to aid effective management of the Nation's ground-water resources by providing information on the hydrology and geochemistry of regional aquifer systems (Bennett, 1979). The Central Valley aquifer project, covering the Central Valley of California, is one of 29 such projects throughout the country and was started because of the long history of ground-water development and the importance of the area's agricultural production to the national economy (Bertoldi, 1979). Specific water-quality information needed for effective management in the future includes (1) the general inorganic chemical character of water from aquifers currently in use, (2) delineation of areas where degradation is occurring and where degradation may occur in the future, (3) the changes that have occurred in ground-water quality with time, and (4) the processes that control ground-water chemistry. This report evaluates temporal changes and geochemical processes as they influence the chemical quality of shallow ground water in the Sacramento Valley, the northern third of California's Central Valley. A companion report (Fogelman, 1983) deals with spatial variations in the chemical character of ground water and the delineation of areas of potential water-quality problems for this same study region.

DATA COMPILATION

Collection of additional water-quality samples was unnecessary because of the extensive data base of the U.S. Geological Survey and California Department of Water Resources. Chemical analyses from 653 wells throughout the Sacramento Valley sampled by the Geological Survey between 1974 and 1976 were already in the Survey's water-quality file (Fogelman, 1975, 1976; Fogelman and Rockwell, 1977). From the unpublished files of the California Department of Water Resources, an additional 2,136 analyses from 281 wells were added to the water-quality file. During the summer of 1979, 63 additional samples were collected by the Geological Survey in Yolo County to extend coverage into an area where high boron concentrations suggested a need for water-quality evaluation. All wells from which chemical analyses were used in this study have driller's logs on file with the California Department of Water Resources. Thus, reasonably reliable information is available about depths and perforated intervals for these wells. Some of the samples represented multiple observations over time from single wells, and these were used for the temporal studies. Samples for the period 1974–79 were examined, and complete analyses with less than 5 percent error in the electrical balance between cations and anions were used to study the spatial variation in the valley. These latter data consisted of 671 analyses from 651 wells.

Manipulation of data files and the statistical analyses used in this report were accomplished using the Statistical Analysis System (SAS)[1] programs on the U.S. Geological Survey's Reston computer system.

WELL-NUMBERING SYSTEM

Wells are identified according to their location in the rectangular system used for the subdivision of public lands. The identification consists of the township number, north or south; the range number, east or west; and the section number. A section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with A in the northeast corner of the section and progressing in a sinusoidal manner to R in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian relative to which the townships and ranges are numbered. For the Sacramento Valley, this is the Mount Diablo base line and meridian (M). Figure 2 shows how the well number 11N/02E–23N01M is derived.

ACKNOWLEDGMENTS

The California Department of Water Resources has cooperated with the U.S. Geological Survey in past studies during which much of the data analyzed in this report were collected. The Department also provided additional unpublished chemical-quality data from their files. The author would like to thank J. R. Slack of the Geological Survey for his helpful suggestions on trend analysis. The cooperation of the residents of the Central Valley who have permitted the Geological Survey to collect water samples from their wells is also appreciated.

DESCRIPTION OF THE STUDY AREA

GEOLOGY AND GEOMORPHOLOGY

The Geology and geomorphology of the Sacramento Valley have been covered in detail by Olmsted and Davis (1961), the California Division of Mines and Geol-

[1]Use of trade names does not imply endorsement and is used for information only.

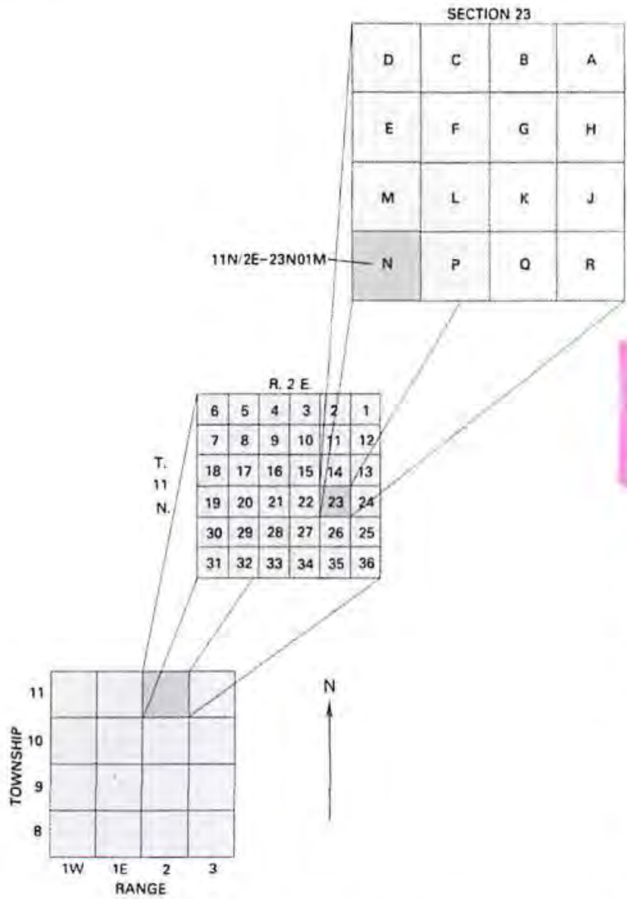

FIGURE 2.—Well-numbering system.

ogy (1966), and the California Department of Water Resources (1978a). Detailed maps and complete descriptions of the geology can be found in these publications. In this section, the geology and geomorphology are only briefly reviewed, with particular attention given to water-bearing characteristics and importance for water quality.

GEOLOGIC SYNOPSIS

The Sacramento Valley is an elongated structural trough trending to the northwest through central California. The trough is filled with a thick accumulation of sediments, perhaps as much as 50,000 feet in the deepest parts. Deposition has been occurring since early in the Cretaceous Period, with the bulk of the deposition occurring in a marine environment. A maximum of only 3,000 feet of continental deposits has been laid down as a veneer over the marine sediments. During early Tertiary time, the Cretaceous sediments west of the valley were folded and uplifted, forming the Coast Ranges and isolating the Sacramento Valley from the ocean to the west.

Early- and middle-Tertiary sedimentation was primarily confined to the southern and eastern parts of the valley, with only those sediments adjacent to the Sierra Nevada being continental deposits. During late Tertiary time, continental deposits were laid down throughout the valley, and deposition continued into Quaternary time. These continental deposits include the Tehama, Tuscan, Laguna, and Mehrten Formations and form some of the most important aquifers in the valley. Also, near the end of the Tertiary Period, andesitic lava was extruded through the older marine sediments to form Sutter Buttes, a prominent volcanic neck in the middle of the Sacramento Valley.

During Pleistocene time, continental deposition continued throughout the valley. Alluvial fans and plains developed from sediments eroded from the Sierra Nevada to the east and the Coast Ranges to the west. Continued action of rivers flowing through the valley produced alluvial channel deposits and natural levees along the axis of the valley and produced flood basins adjacent to the rivers.

GEOMORPHIC UNITS

The Sacramento Valley is generally characterized by alluvial plains and fans bounded by rugged mountains. The geomorphic units described by Olmsted and Davis (1961) are (1) Sierra Nevada, (2) Coast Ranges, (3) Cascade Range, (4) low hills and dissected uplands, (5) alluvial plains and fans, (6) flood basins, (7) stream channels and natural levees, and (8) Sutter Buttes. In this section, the location and extent of the geomorphic units are described, and the geologic formations composing each unit discussed. Attention will be given to the lithology, mineralogy, and water-bearing characteristics of the geologic units where information is avaliable. The location of the geomorphic units are illustrated on plate 1A.

(1) *Sierra Nevada*. The Sacramento Valley is bounded on the east by the mountainous Sierra Nevada, a massive block of the Earth's crust that has been uplifted and tilted westward. The block extends under the sediments of the valley and underlies the eastern part at depth. The Sierra Nevada is composed of intrusive igneous rocks, metamorphosed volcanic rocks, and Paleozoic sedimentary rocks. The intrusive rocks are mainly granodiorite and quartz diorite with andesitic and rhyolitic extrusive rocks. In addition to the feldspars, quartz, and biotite of the igneous rocks, a wide variety of other minerals is present. These include cal-

cite, magnesite, barite, serpentine, metal sulfides, and others. The massive rocks of the Sierra Nevada contain little water, with the little that is available occurring in joints and fractures. The water quality of streams draining the Sierra Nevada is generally very good.

(2) *Coast Ranges*. The Coast Ranges, adjacent to the west of the valley, consist of Cretaceous marine sedimentary rocks folded and uplifted into ridges trending northwest-southeast, parallel to the valley. The Cretaceous rocks dip eastward and underlie much of the Sacramento Valley at depth. Also present in the Coast Ranges is the Franciscan Complex, which consists of highly metamorphosed marine sedimentary rocks of late Mesozoic age. The major rock type is this geologic unit is greywacke, interbedded with shales and minor limestone units. The primary minerals of the sedimentary rocks are plagioclase and quartz. Many lithic fragments present contain chert, chlorite, and mica. Ultramafic minerals have been metamorphosed to serpentine and magnesite. The marine sedimentary rocks are mostly consolidated and contain little water. Some units retain connate saline water, and streams draining the Coast Ranges may be contaminated by saline springs.

(3) *Cascade Range*. Between Oroville and Red Bluff, the northeastern part of the Sacramento Valley is bounded by the Cascade Range geomorphic unit. Adjacent to the valley, this unit is composed of the gently southwestward dipping Tuscan Formation of Pliocene age. On the surface, the Tuscan Formation is extensively eroded, and southwestward flowing streams have incised deep canyons. Beneath the valley, the Tuscan extends westward under younger valley sediments as far as the Sacramento River, and there the Tuscan interfingers with the Tehama Formation. The Tuscan is composed of volcanic breccia, coarse- to fine-grained tuffs, and volcanic sands, all of primarily andesitic composition. The most abundant mineral in the black sands found in wells drilled into this unit is plagioclase, and accessory quartz and pyroxenes. Volcanic glass is also abundant from the mudflow and tuff deposits. The Tuscan is an important aquifer in the northeastern part of the valley, and it contains fresh water at all depths.

(4a) *Low hills and dissected uplands, east side*. The dissected alluvial uplands leading up to the Sierra Nevada on the east side of the valley are composed of Tertiary and lower Quaternary sediments. This gently rolling terrain merges with the foothills of the Sierra Nevada to the east and the low alluvial plains to the west. The oldest rocks here are of the Eocene Ione Formation, overlain by the Oligocene, Miocene, and Pliocene volcanic deposits of the Valley Springs and Mehrten Formations. These units extend westward to the trough of the valley, but they are generally too deep to be tapped as aquifers except in the foothills area. Overlying the volcanic sediments are upper Tertiary and Quarternary continental deposits eroded from the Sierra Nevada. The older Tertiary volcanic sediments are composites of volcanic sands, ash and mudflows, and tuff layers of rhyolitic and andesitic composition. Particular minerals noted in these units include biotite, hornblende, orthoclase, plagioclase, and quartz. The Ione Formation contains kaolinitic clay layers. The younger deposits, the Laguna Formation and Fair Oaks Formation of Shlemon (1967), are sand, gravel, and silt deposits intercalated by clay layers. The Quaternary deposits are poorly sorted, and wells finished in these units produce only moderate quantities of water.

(4b) *Low hills and dissected uplands, northeast*. The low hills on the northeast margin of the valley consist of reworked sediments eroded from the underlying Tuscan Formation. The hills show the characteristic form of alluvial fans but are deeply trenched by the streams draining the Cascade Range. These fanglomerate deposits, as they are called, are mainly cemented sands, gravels, and silts, and have a mineral composition similar to that of the Tuscan Formation from which they are derived. The fanglomerate is also an important source of water in this area.

(4c) *Low hills and dissected uplands, west side*. The low hills on the west side of the valley are composed of the Tehama Formation of Pliocene age. These deposits extend from Red Bluff on the north almost as far south as Fairfield. The Tehama is made up of poorly sorted fluviatile sediments, primarily beds of sandy silt and silty clay with some lenses of crossbedded sands and gravels. Many of the coarser layers are cemented by calcium carbonate that reduces their permeability. The Tehama extends eastward to about the middle of the valley and is generally within 150 to 200 feet of land surface. Tectonic activity since deposition has folded the Tehama into a number of structures such as the Dunnigan Hills, Corning Ridge, and Plainfield Ridge along the valley margin. Sediments originated in the Coast Ranges and are rich in plagioclase and magnesium silicates, such as chlorite and serpentine. The Tehama is an important potential aquifer, although currently most water is the area is being pumped from more permeable alluvial fan deposits nearer the surface.

(5a) *Alluvial plains and fans, east side*. The alluvial plain on the east side of the valley is referred to as the Victor Plain by Olmsted and Davis (1961). The Victor Formation[2] of Olmsted and Davis (1961), which

[2]Recent work of Marchand and Allwardt (1981, p. 207) virtually eliminates the use of the Victor Formation for the northeastern part of the San Joaquin Valley. However, because no similar recent work has been done in the Sacramento Valley, the Victor Formation as defined and mapped by Olmsted and Davis (1961, p. 93) is used in this report.

ranges in thickness from 50 to 100 feet, covers the surface throughout the area and overlies the Laguna Formation, a Pleistocene continental deposit. The plain extends from the northern San Joaquin Valley to north of Chico, where it pinches out between the fanglomerate of the Cascade Range and the Sacramento River flood plain. The Victor Formation is composed of alluvial sediments carried down from the Sierra Nevada and contains numerous channel deposits. The sediments become generally finer grained towards the west with bluish- and greenish-gray clays indicating reducing deposition environments near the center of the valley. Opposite the Sierra Nevada, the material contains extensively weathered feldspars, quartz, mica, biotite, and layers of arkosic sandstones. Opposite the Cascade Range, the Victor Formation is composed of reworked volcanic detritus from the Tuscan Formation. Water is generally available throughout the Victor Formation, though many high-capacity irrigation wells also tap the underlying Laguna Formation.

(5b) *Alluvial plains and fans, west side.* The low alluvial fans on the west side of the valley have been laid down by streams draining the Coast Ranges. The fans are aggrading and have poorly developed soil horizons. The northernmost fan is that of Stony Creek, which extends from the valley margin to the Sacramento River. South of this fan, a series of small fans built up by ephemeral streams extends only a short distance away from the Coast Ranges. Cache Creek and Putah Creek, south of the Dunnigan Hills, also have developed rather large fans which coalesce to form Putah Plain. The lithology of these fans is varied but generally is coarse-grained and poorly sorted. The mineralogy reflects the source areas in the Coast Ranges. The alluvial fans are generally good aquifers, especially where old stream channel deposits are penetrated.

(6) *Flood basins.* Low areas adjacent to the Sacramento River were subject to frequent flooding before extensive construction of levees in modern times. In these basins, fine-grained sediments have settled out of flood waters to form poorly permeable deposits. Deposits between 50 and 170 feet thick of yellow clay, indicating oxidizing conditions, overlie blue clays reflecting reducing conditions at depth. Few wells are drilled in these areas, and the only water generally available is in tongues of sand and gravel from old channel deposits.

In Sutter Basin, ground water contains high chloride concentrations and is unsuitable for irrigation purposes. The origin of this high chloride water is thought to be from Cretaceous marine sedimentary rocks brought closer to the surface by faulting associated with the formation of Sutter Buttes.

(7) *Stream channels and natural levees.* Along the major rivers and streams throughout the valley, Holocene alluvial deposits form flood plains and natural levees. The levees slope gently away from the channels and merge into the surrounding flood basin deposits. The deposits are generally coarse grained and poorly sorted. The varied mineralogy reflects the many sources from which these sediments are derived. Wells drilled in these deposits are hydraulically connected to the adjacent rivers and can produce large quantities of water.

(8) *Sutter Buttes.* Sutter Buttes, a volcanic neck of late Tertiary age, rises abruptly 2,100 feet above the surrounding plains. The core of the buttes is andesite, surrounded by alluvial fans created from the erosion of the igneous rocks. The deposits are poorly sorted and contain tuff, volcanic breccia, and sands. Some Cretaceous marine sedimentary rocks exposed at the buttes were forced upwards by the rising lava. The volcanic rocks yield little water, but the adjoining alluvium produces moderate amounts.

HYDROGEOLOGY

The direction of ground-water movement can be determined from the configuration of the water table where ground water occurs in saturated sediments and is not confined. Ground-water movement is influenced by gravity, and so is downhill as determined by the altitude of the water table. Plate 1*B* is a map showing lines of equal altitude of the water table for the Sacramento Valley in the spring of 1975. Although extensive changes occurred in some areas during the drought of 1976 and 1977, the 1975 map reflects the general conditions throughout the valley as they existed when most of the water-quality samples were collected during the mid-1970's.

In the north part of the valley, ground waters flow to the south and away from the valley walls. The Sacramento River is a gaining stream north of Colusa and is a major ground-water discharge zone in the north part of the valley. Stony Creek alluvial fan is a particularly important area for recharge. South of Colusa, the Sacramento River becomes a losing stream, contributing water to the adjacent sediments. In the west-central part of the valley, between Colusa and Woodland, recharge from the west infiltrates the valley sediments and moves toward pumping depressions east of the Dunnigan Hills. In the east-central part of the valley, from Oroville to Marysville, the Feather, Yuba, and Bear Rivers recharge the ground water near the valley margin. Once on the valley floor, the Feather River becomes a gaining stream east of Sutter Buttes, but below Marysville it begins to lose water to pumping depressions to the east and west. A large pumping depression in the southeast draws water from the American and Sacramento Rivers in the vicinity of Sacramento. In the southwest, much ground-water recharge occurs in the Cache and Putah Creek alluvial fans. This water moves eastward toward pumping depressions near Woodland and Davis. Some recharge from Cache Creek flows around the end of the Dunnigan Hills to pumping depressions north of Woodland.

The water table in the Sacramento Valley is generally close to the surface, and in only a few places is it more than 80 feet below the surface. Depth to water in the flood basins and alluvium along the Sacramento and Feather Rivers ranges from 10 to 20 feet. This very shallow water table extends eastward to include much of the western part of the Victor Plain. In the alluvial fans along the west side of the valley, the depth to water is between 10 and 40 feet. Lowering of water levels in pumping depressions north of Woodland and south of Davis, however, has increased the depth to water in those places. Along the southeast margin of the valley, the depth to water increases from less than 10 feet, near the flood basins, to more than 80 feet in the foothills. In the fanglomerate of the Cascade Range around Chico, the depth to water is generally 10 to 40 feet.

The valley boundary illustrated on plate 1*B* is the approximate boundary of the principal alluvial aquifers currently used in the Sacramento Valley. There is no single definition of the Sacramento Valley, and different boundaries are drawn for different purposes. The boundary shown is approximately that used in a ground-water-flow model of the Sacramento Valley (California Department of Water Resources, 1978a, Appendix A). However, the definition of the Sacramento Valley ground-water basin by the State of California encompasses a much larger area. The boundary is a reference shape to show continuity among illustrations.

On the east side of the valley, the margin coincides with the contact between the alluvium of the low hills and dissected uplands geomorphic province, and the older rocks of the Sierra Nevada and Cascade Range provinces. On the west side, the division is at the contact between the younger alluvium of the alluvial fans and plains, and the older alluvium of the low hills and dissected uplands geomorphic province. This allows delineation of the Dunnigan Hills, and excludes a large, undeveloped and sparsely populated area to the northwest of the valley.

Some wells outside the principal alluvial aquifers were included in the data analysis, as the boundary of those aquifers is somewhat arbitrary. Because these wells lie in recharge zones, their characteristics are important to an understanding of ground-water chemistry in the rest of the valley, even though they are outside the area of the principal alluvial aquifers.

HYDROCHEMICAL FACIES

The concept of hydrochemical facies as described by Back (1966) is used to designate zones or areas in which ground waters share unique chemical characteristics. The differences between facies reflect different controls on water chemistry from the lithology and mineralogy of, flow patterns in, and sources of recharge to an aquifer. The prefix "hydro" is used as a modifier of "chemical" to emphasize the interdependence of chemistry and hydrology. The ground water in the Sacramento Valley shows a great diversity in chemical compositions. By dividing the valley into hydrochemical facies, the differences can be better related to differences in the sedimentary matrix holding the water and the sources of ground-water recharge.

CRITERIA AND PROCEDURE FOR DIVISION

While hydrochemical facies have commonly been defined in terms of water types (as determined by the predominance of ions in terms of equivalents per million; Back, 1966), the definition of hydrochemical facies can be based on any unique chemical signature. For the Sacramento Valley, this division was accomplished using differences in the concentrations of some of the dissolved chemical constituents.

An initial division of the valley was attempted by studying maps showing the geomorphic units, the water table, and the distribution of individual chemical constituents. Outlines of these areas were drawn up to the nearest quarter township, and a tentative hydrochemical facies was determined for each well. This initial division broke the valley into three areas extending northwest-southeast, parallel to the axes of the valley—along the west side, the east side, and in the central basins. Each of these areas was divided into a northern and southern part resulting in six tentative divisions.

After this initial division, these six areas were tested to determine if they could be successfully differentiated on the basis of their chemistries. Linear discriminant function analysis (Davis, 1973; Drake and Harmon, 1973) was used for this purpose. In linear discriminant function analysis, a linear combination of variables is used to distinguish between previously defined groups. After the function is defined, it can be used to classify new samples of unknown origin into one of the original groups.

To determine which chemical constituents would be the best to use in the discriminant analysis, the amount of variation in the major chemical species associated with the differences between hydrochemical facies was determined. The results of this analysis of variance are shown in table 1. The first five species in this table

TABLE 1.—*Variation in chemical constituents explained by variations between hydrochemical facies*

Constituent	Percent variation explained
Silica	62.7
Boron	48.5
Sodium	44.7
Bicarbonate	39.4
Nitrate	36.8
Chloride	30.1
Magnesium	27.2
Calcium	15.1
Sulfate	9.6

were picked for the analysis. Because chloride is closely associated with sodium in the valley, it was passed over and magnesium added to give a total of six chemical constituents to use in the discriminant analysis.

Of the 671 chemical analyses available, only 340 had measurements for all the species and could therefore be used in the analysis. Most of the reduction in sample size was due to the much smaller number (358) of silica analyses. However, because silica showed by far the greatest amount of variation between the tentative hydrochemical facies, it was decided to use silica at the cost of reducing the number of samples that could be classified using the discriminant function. Samples, which lack measurements of all six of the chemical species used, were subsequently classified on the basis of nearby wells.

About one-fifth of the eligible samples were used to define the discriminant functions for the six hydrochemical facies. Using these functions, the remaining eligible samples were classified using the chemistry, and this classification was compared to the prior classification from the map data. Misclassified observations were of two types. Type 1 misclassifications were scattered throughout other facies and showed no pattern nor were particularly close to the boundary between two areas.Type 2 misclassifications were clustered in an adjacent hydrochemical facies near the boundary. In the latter case, the boundaries were redrawn and the chemical analyses reclassified.

The discriminant functions were recalculated several times with adjustments in boundaries between each calculation. The final analysis showed that 76 percent of the samples could be correctly classified by hydrochemical unit using the six chemical species. Thirteen percent of the samples were misclassified into the adjacent northern or southern portion in the same part of the valley, indicating an association between west side, east side, and basin pairs. On the basis of the classification of wells in a quarter township, each quarter township was assigned to its final hydrochemical facies. Other wells missing some of the chemical species used for the classification were classified by their quarter township location.

The discriminant analysis showed that enough chemical variation existed among the six hydrochemical facies to consider them chemically distinct. The final boundaries of the hydrochemical facies are shown on plate *1B*. On the east side of the valley, one of the facies lies opposite the Cascade Range, and one opposite the Sierra Nevada. The flood basins along the axis of the valley are divided into two more facies, one in Butte Basin and including Sutter Buttes, the second in the Colusa, Sutter, and American Basins. The final two hydrochemical facies are opposite the Coast Ranges and are divided north and south near Colusa. In the next section, the chemical characteristics of the six hydrochemical facies are presented and compared, and differences in chemistry are discussed.

DESCRIPTIONS OF HYDROCHEMICAL FACIES

Table 2 shows the geometric mean, minimum, and maximum of chemical concentrations for each of the hydrochemical facies. To determine if the average concentrations of chemical species in the hydrochemical facies are significantly different, the differences between geometric means were tested using a t test. The results of these comparisons are illustrated quantitatively in the same table.

TUSCAN VOLCANIC ROCKS

The Tuscan volcanic rocks hydrochemical facies is along the northeastern margin of the Sacramento Valley (pl. *1B*) adjacent to the Cascade Range. The geologic formations in this area are the Tuscan Formation and more recent alluvial sediments derived from erosion of the Tuscan. Recharge is from the Cascade Range geomorphic province, and ground water is either discharged to the Sacramento River or moves into Butte Basin south of Chico. The Tuscan and its derivatives contain andesitic sands and extensive tuff deposits. Volcanic glass and plagioclase are abundant in these sediments.

The chemistry of ground water in the area reflects the low concentrations of dissolved solids carried by recharge from the Cascade Range, having low mean concentrations of magnesium, sodium, bicarbonate, sulfate, and chloride. Silica concentrations are high due to solution of volcanic glass, and the facies has the highest average nitrate-nitrogen concentration of the six. The maximum boron concentration is rather high, although the mean concentration is only moderate. Boron in excess of 1.0 mg/L occurs in only three wells, all to the east of the Sacramento River northeast of Red Bluff.

TABLE 2.—*Geometric mean, minimum, and maximum of chemical concentrations for each of the hydrochemical facies, Sacramento Valley*

[Figure above line refers to geometric mean; figures below line refer to minimum-maximum range. H, high; L, low; VH, very high; VL, very low. NOTE.—These comparisons are relative to the other hydrochemical facies and do not necessarily describe the absolute values. Labels were assigned only where the difference between two geometric means tested significant at the 95 percent level]

Chemical species	Tuscan volcanic rocks		Victor Plain		Butte Basin		Sutter Basin		North alluvial fans		South alluvial fans	
Dissolved solids (mg/L)	L	231 / 137–571	L	220 / 137–1100		290 / 129–723	H	400 / 97–2040		280 / 108–1170	H	400 / 175–1420
Calcium (mg/L)		26 / 14–75	L	21 / 5.7–170		32 / 5.5–98		32 / 6.9–220	H	39 / 8.2–99	H	39 / 13–140
Magnesium (mg/L)	L	19 / 9.1–60	VL	12 / 3.6–120		24 / 5.0–93		24 / 2.2–160		24 / 7.6–70	H	33 / 3.5–140
Sodium (mg/L)	L	14 / 3.9–68		19 / 7.2–180		20 / 6.3–93	H	55 / 5.9–360		22 / 7.5–240	H	52 / 15–320
Potassium (mg/L)		1.3 / 0.3–5.9		1.3 / 0.4–4.5	H	1.9 / 0.6–5.0	H	1.7 / 0.3–5.4	L	0.8 / 0.4–2.1		1.2 / 0.2–7.0
Bicarbonate (mg/L)	L	170 / 98–400	VL	130 / 68–504		230 / 44–522	H	270 / 70–897		240 / 83–560	VH	310 / 130–1060
Sulfate (mg/L)	L	8.1 / 0.0–71	L	8.0 / 0.2–140		12 / 0.5–150		17 / 0.3–590		18 / 1.6–400		21 / 1.8–180
Chloride (mg/L)	VL	6.5 / 0.9–97		15 / 2.0–380	L	11 / 1.0–210	H	31 / 2.4–920		15 / 2.7–170	H	37 / 2.2–580
Fluoride (mg/L)		0.11 / 0.1–0.3		0.18 / 0.1–10.0		0.12 / 0.1–0.3		0.11 / 0.0–0.4		0.16 / 0.0–0.6	H	0.29 / 0.1–1.0
Nitrate - N (mg/L)	H	2.7 / 0.2–27		0.81 / 0–61		1.0 / 0–20	L	0.12 / 0–14		1.7 / 0.01–11		1.8 / 0–12
Phosphate - P (mg/L)		0.05 / 0.0–0.31		0.11 / 0.01–0.39		0.11 / 0.01–0.45		0.15 / 0.01–0.50		0.06 / 0.02–0.30		0.07 / 0.01–0.42
Silica (mg/L)	H	51 / 35–67	H	55 / 25–74	H	51 / 31–75		39 / 23–73	L	26 / 8.5–52	L	28 / 12–54
Iron (μg/L)		4.8 / 0–170		5.2 / 0–600		8.0 / 0–1900	H	11 / 0–520		9.7 / 0–280		8.0 / 0–180
Manganese (μg/L)		3.4 / 0–10		5.6 / 0–280		9.1 / 0–1700	H	75 / 0–2300		8.0 / 0–70		2.8 / 0–2000
Arsenic (μg/L)		1.2 / 0–4		2.2 / 0–20	H	5.5 / 0–50	H	5.8 / 0–100		1.7 / 0–6		2.3 / 0–31
Boron (mg/L)		0.066 / 0–1.50	L	0.023 / 0–0.60	L	0.034 / 0–0.37	H	0.140 / 0–1.10		0.068 / 0–0.58	VH	0.400 / 0–8.10

The source of the high boron water is Tuscan Spring, located along Salt Creek in Tehama County in section 32 of township 28 N., range 2 W. (Waring, 1965).

VICTOR PLAIN

The Victor Plain hydrochemical facies is along the east and southeast margin of the valley, and extends westward to near the Feather and Sacramento Rivers. Recharge is primarily from the Sierra Nevada to the east, although pumping depressions southeast of Marysville and north of Sacramento induce recharge from the rivers. North of Marysville, water is discharged into the Feather River or passed into Butte Basin. South of Marysville, most of the ground-water discharge seems to be by pumping. Along the valley margin, the aquifers are volcanic sands with associated tuffaceous deposits. In the central and western parts of this facies, the volcanic units dip under the Victor Formation composed of alluvium from the Sierra Nevada.

The Victor Plain facies has a low average dissolved-solids content reflecting recharge from the Sierra Nevada. Concentrations of calcium, magnesium, bicarbonate, boron, and sulfate are all low in this area. Silica is high, reflecting the volcanic material present in the sediments.

BUTTE BASIN

The Butte Basin hydrochemical facies roughly coincides with the Butte flood basin east of the Sacramento River. The basin extends from Chico on the north to Yuba City on the south and lies between the Feather and Sacramento Rivers. Sutter Buttes is included in this facies as too few chemical analyses were available from this area to justify a separate facies. The basin receives recharge from the Tuscan volcanic rocks facies and from Victor Plain to the east. A small amount of recharge also occurs in the vicinity of Sutter Buttes. Ground water leaves the Butte Basin facies to enter the Sacramento River and to enter the Sutter Basin facies east of Sutter Buttes. In the flood basins the sediments are fine grained and reducing.

Ground water in the Butte Basin facies has a somewhat higher average dissolved-solids concentration than the two eastern margin facies possibly reflecting longer subsurface residence times or a change in sediment lithology. Chloride and boron are the only two species that have low average concentrations in this facies. The high silica concentrations may be a result of recharge from the Tuscan volcanic rocks facies and from volcanic material around Sutter Buttes. High arsenic concentrations imply deposition in a reducing environment (Garrels and Christ, 1965). This facies has the highest average potassium concentration, which may reflect the longer residence times or a change in mineralogy of the sediments.

Information on the variation in water chemistry with depth was obtained from a U.S. Geological Survey test well drilled in section 32 of township 19 N., range 1 W. Three piezometer tubes were installed at different depths and isolated by cement packers. Data on the shallow water at the site are available from a previous study (Fogelman, 1976).

Analyses from the three piezometers and from the shallow water are shown in table 3. The percent composition of the major ionic species in terms of milliequivalents per liter are provided in figure 3. Between 80 and 595 feet, a decrease in magnesium is balanced by an increase in sodium, with calcium remaining about the same. There is a slight increase in the percent of chloride in the ground water over this same interval, but the net change in anion composition is very small. Below 595 feet, however, calcium and magnesium decrease, both in percent composition and concentration, and sodium increases. Chloride also increases, becoming the dominant anion by a depth of 968 feet. Even at 1,333 feet, however, the dissolved-solids concentration of the water is only moderate, at 526 mg/L, and the boron concentration remains low.

SUTTER BASIN

The Sutter Basin hydrochemical facies is between the Sacramento and Feather Rivers south of Sutter Buttes. This facies extends west of the Sacramento River near Colusa to include part of Colusa Basin and includes some of the American Basin east of the Feather River. Recharge comes from Sutter Buttes, from the Butte Basin hydrochemical facies east of Sutter Buttes, and from both the Sacramento and Feather Rivers. Sediments in the flood basins are generally fine grained and reducing at depth.

The Sutter Basin facies is tied with the south alluvial fans facies for the highest average dissolved-solids concentration. This facies is also high in sodium, chloride, bicarbonate, potassium, and boron. The effects of reducing conditions are evident in the relatively higher concentrations of iron, manganese, and arsenic in this area, all of which are more soluble in reducing environments (Garrels and Christ, 1965). The very low average nitrate concentration in this facies is also indicative of reducing conditions, where nitrate can be removed by denitrification reactions.

The origin of the high dissolved-solids water is thought to be connate marine water moving upward along fault zones created when Sutter Buttes was emplaced (Curtin, 1971). Throughout much of the southern part of Sutter Basin, water of very high salinity (specific conductance greater than 3,000 micromhos) is located within 400 feet of the surface.

TABLE 3.—*Chemical composition of water from wells of various depths, section 32 of township 19 N., range 1 W.*

Sample No. (fig. 3)	Site identification	Depth of well (feet)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Nitrate-N (mg/L)	Boron (mg/L)	Dissolved solids (mg/L)
1	19N/01W–32A01M	80	28	24	34	260	12	12	0.59	0.12	276
2	19N/01W–32G03M	595	25	4.4	62	210	12	22	.03	.15	276
3	19N/01W–32G02M	968	12	2.6	110	150	3.6	110	.02	.18	340
4	19N/01W–32G01M	1,333	15	2.8	160	110	3.4	230	.12	.24	526

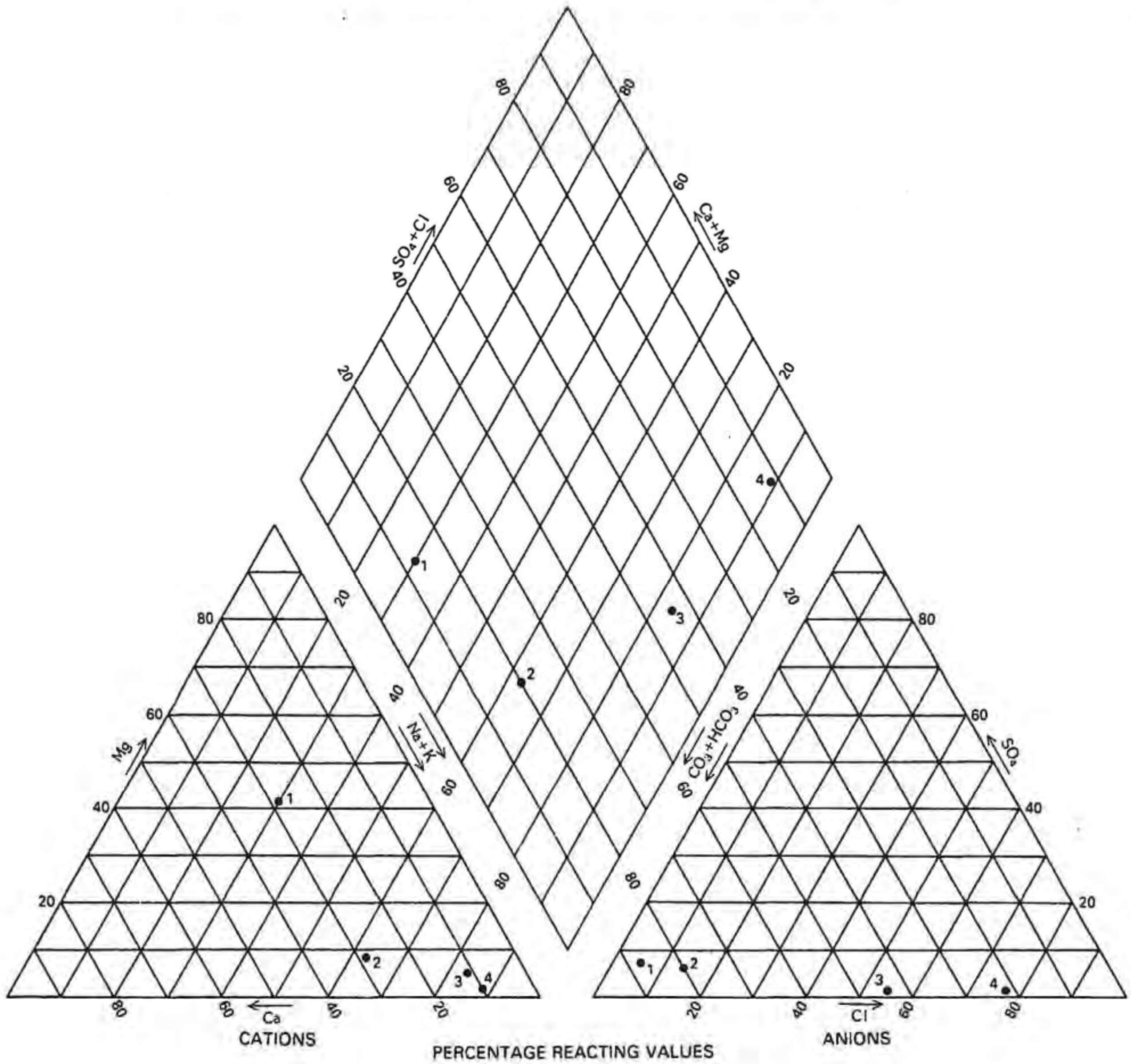

FIGURE 3.—Major-ion composition of water from wells of various depths in section 32 of township 19 N., range 1 W. Numbers refer to sample numbers in table 3.

NORTH ALLUVIAL FANS

The north alluvial fans hydrochemical facies is along the northwestern margin of the valley. Ground water occurs primarily in alluvial fan deposits and is recharged by streams draining the Coast Ranges. The alluvial fan of Stony Creek is a major source of recharge in this area, with flow radiating away from the fan to the north, east, and south. Ground-water flow in this facies is generally east and south. Most of the water is discharged to the Sacramento River along the eastern margin of the facies, although some moves into Colusa Basin along the southern boundary. Sediments in the alluvial fans are primarily derived from Mesozoic marine rocks of the Coast Ranges with sediments derived from Franciscan metamorphic rocks carried down by some of the larger streams.

The average dissolved-solids concentration in the north alluvial fans facies is moderate, and most of the chemical-constituent averages fall between those of the other facies. Calcium is the only species with a high average concentration in this facies; this is from the waters of Stony Creek, which are high in calcium. Silica is much lower in waters on the west side of the valley, and this is shown by the low average silica concentration.

SOUTH ALLUVIAL FANS

Located along the southwestern margin of the valley in alluvial fans adjacent to the Coast Ranges, the south alluvial fans hydrochemical facies extends from Putah Creek north to township 15 N. Recharge from the Coast Ranges is provided by numerous ephemeral streams north of township 10 N., and by Cache and Putah Creeks in townships south of 11 N. Recharge from Cache Creek moves around the end of the Dunnigan Hills to pumping depressions north of Woodland. Some recharge is also drawn from the Sacramento River to these same pumping depressions.

The south alluvial fans hydrochemical facies is distinguished by having high average concentrations for many of the chemical species measured. Dissolved solids, calcium, magnesium, sodium, chloride, and fluoride all have high average concentrations here. Boron and bicarbonate concentrations in this facies average very high. With little volcanic material to provide silica, its average concentration is low, as in the north alluvial fans.

Boron and chloride concentrations in the ground water of this facies average the highest in the valley, and boron concentrations as high as 8.1 mg/L have been measured in township 11 N., range 2 E. The source of the chloride and boron has been attributed to the streams draining the Coast Ranges (Bertoldi, 1976). Information obtained from a deep test well drilled by the U.S. Geological Survey in section 34 of township 12 N., range 1 E., indicated another possible source. The test well 12N/01E–34Q was drilled to a total depth of 2,400 feet and piezometers tubes installed at 942 feet, 1,396 feet, and 2,120 feet. No sample was obtained from the 942-foot depth, but analyses from the two deeper piezometers are shown in table 4. At a depth of 2,120 feet, water containing 12 mg/L boron and 660 mg/L chloride was encountered. Piezometric heads in the test well indicate upward movement of water, which may be contaminating the shallow water.

The source of boron and chloride in the streams draining the Coast Ranges is warm saline springs, a number of which occur in the Clear Lake area. Partial chemical analyses from these springs are also shown in table 4. Boron concentrations are as high as 310 mg/L in these springs. To determine the source of the high boron concentrations in the ground water in township 11 N., range 2 E., the percent composition in milliequivalents per liter of the wells in this township were plotted along with the deep well water and the warm spring water (fig. 4). The Wilbur Oil Test is a wildcat oil well that produces cold water also high in boron and chloride.

TABLE 4.—*Data for wells and springs plotted in figures 4 and 5*

[Samples 1–2 from U.S. Geological Survey test well; 3–9, reported by Fogelman (1976); 10, average for 1960–76; 11–15, reported by White and others (1973), with locations as indicated therein]

Sample No. (fig. 4)	Site identification	Depth to first opening (feet)	Dissolved solids (mg/L)	Chloride (mg/L)	Boron (mg/L)	Temperature (°C)
1	12N/01E–34Q01M	2,120	1,310	660	12	21.0
2	12N/01E–34Q02M	1,396	482	95	1.1	21.5
3	11N/02E–20K06M	387	1,060	210	3.7	20.0
4	11N/02E–18R01M	264	321	39	1.4	18.5
5	11N/02E–18C02M	205	1,470	210	8.1	18.0
6	11N/02E–23N02M	200	746	66	2.5	21.0
7	11N/02E–14B03M	198	307	37	1.1	17.5
8	11N/02E–30C01M	184	741	96	3.3	18.0
9	11N/02E–29A02M	151	816	140	4.8	18.0
10	Cache Creek at Capay	---	268	36	1.5	---
11	Wilbur Springs	---	27,134	9,700	310	55.0
12	Elgin Mine Spring	---	28,872	11,000	240	68.5
13	Abbott Mine Spring	---	7,250	1,900	56	≈30
14	Grizzly Spring	---	12,400	3,940	178	17.5
15	Wilbur Oil Test	---	19,080	11,400	23	21.3

From figure 4 there is no clear indication of whether the water in the wells (sample Nos. 3–9) is derived from the thermal springs (sample Nos. 11–14) or from deep ground water in the area (sample No. 1). Two of the thermal springs, Wilbur Oil Test well and the deep well, are very high in percent sodium. Two of the thermal springs show an increase in percent magnesium, but the percent calcium remains very low.

The deep ground water and the Wilbur Oil Test well have a much higher percentage of chloride than the thermal springs, which are enriched in carbon dioxide from metamorphism at depth (Barnes and others, 1973). As no clear trends emerged in the plot of the percent compositions in milliequivalents per liter, a second plot of chloride versus boron concentrations was made (fig. 5). The dashed diagonal line in figure 5 represents the dilution of Wilbur Springs water with water containing no boron or chloride. The thermal springs all plot very close to this line, having both high chloride and boron concentrations. The shallow wells in township 11 N., range 2 E., all plot very close to the the line representing dilution of Wilbur Springs water, as does the average composition of Cache Creek. Wilbur Oil Test well and the deep wells in the valley plot to the right of the dilution line, which indicates more chloride relative to boron in these waters. From figure 5 the source of the high chloride and boron concentrations is confirmed as water from the thermal springs in the Coast Ranges carried into the valley by streams, such as Cache Creek. Distinct differences between the cold waters,

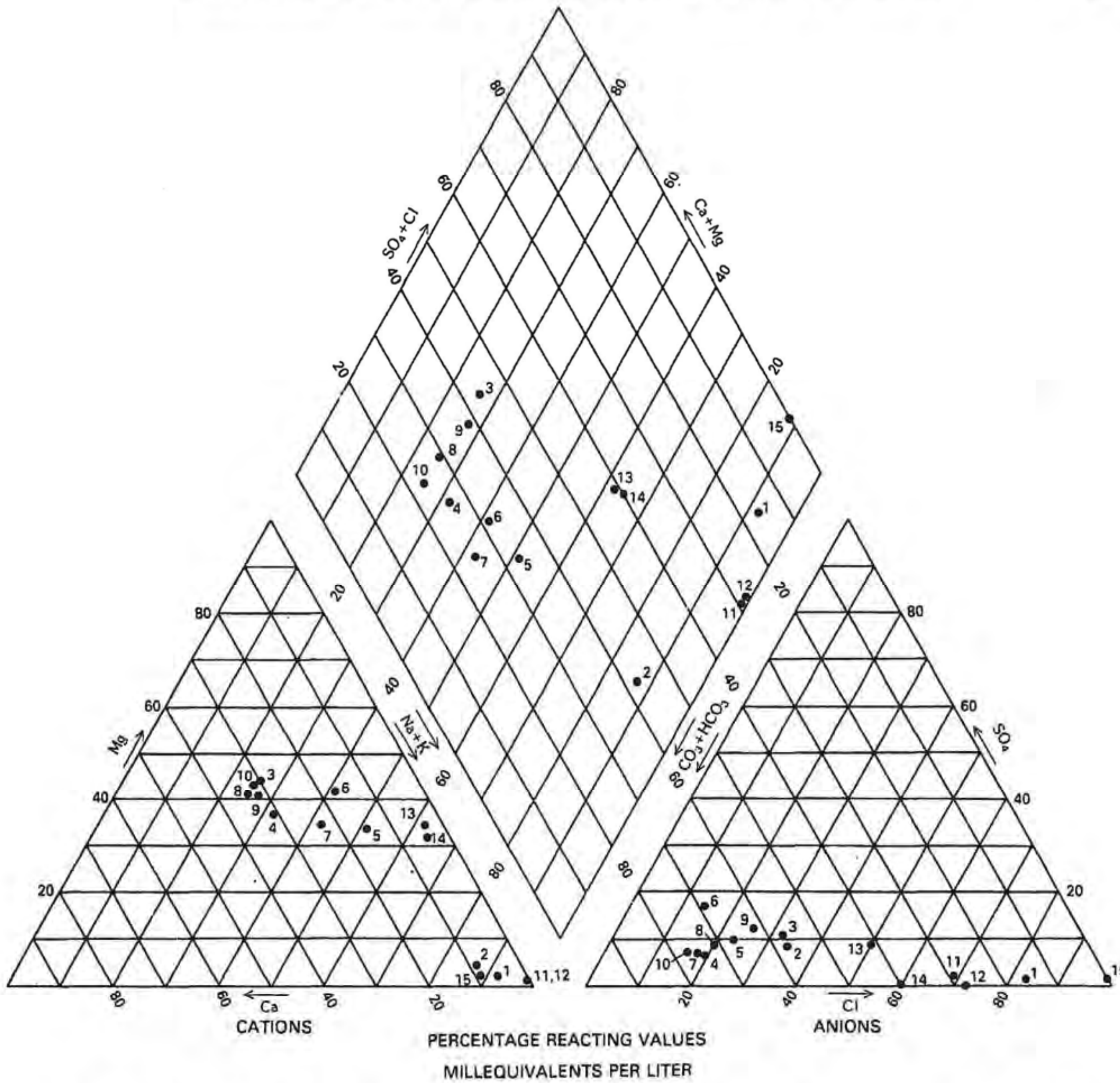

FIGURE 4.—Major-ion composition of water from springs in the Clear Lake area and from wells in a high boron area northwest of Woodland. Numbers refer to sample numbers in table 4.

such as Wilbur Oil Test and well 12N/01E–34Q01, and the thermal waters can be found in the boron-to-chloride ratio and the percent of bicarbonate ion in the waters. The hot waters probably receive inputs of carbon dioxide and boron from a gas phase produced during metamorphism of the marine sediments at depth. Cold waters are not enriched in volatile components and therefore have lower boron-to-chloride ratios and lower percent bicarbonate contents. The shallow wells in township 11 N., range 2 E., have the higher boron-to-chloride ratios indicative of a thermal water source.

TEMPORAL CHANGES

Ground-water-quality degradation may be occurring in the Sacramento Valley because of increasing development accompanied by more intensive agriculture and denser habitation. Such effects have been noted in the

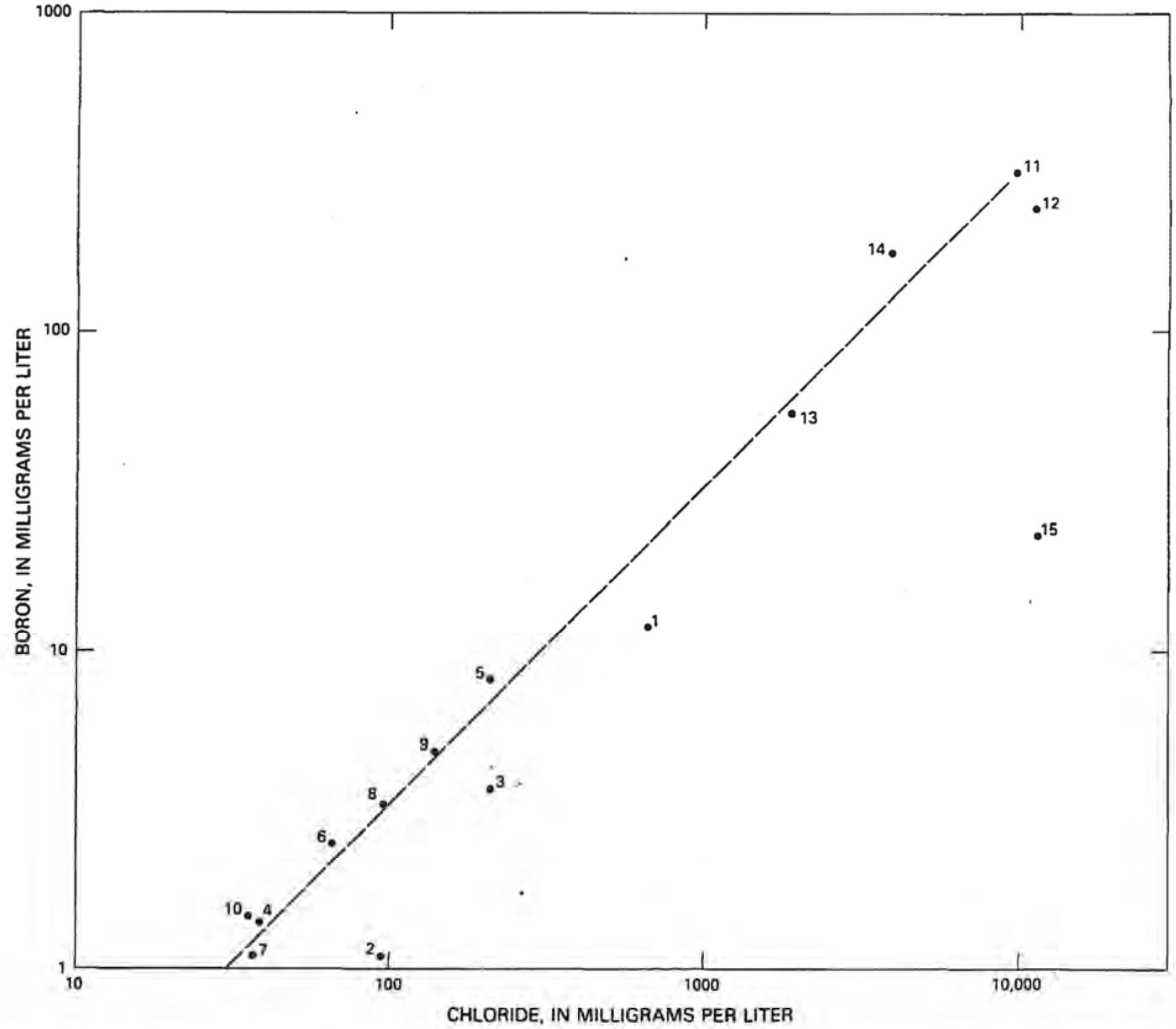

FIGURE 5.—Plot of chloride versus boron for springs in the Clear Lake area and for wells in a high boron area northwest of Woodland. Numbers refer to sample numbers in table 4. Dashed line indicates dilution of Wilbur Springs water with water containing no boron or chloride.

San Joaquin Valley (Kern County Water Agency, 1979), in San Bernardino County (Klein and Bradford, 1979), and in the Colorado River Basin (El-Ashry, 1980). Much of the problem is related to infiltrating irrigation water that (1) has been concentrated by evapotranspiration, (2) has dissolved salts added as fertilizers and soil conditioners, and (3) has leached natural salts from the unsaturated zone. Additional degradation can occur from nonagricultural activities, such as the disposal of sewage and industrial wastes.

In this section, water-quality data from the Sacramento Valley are examined for linear trends with time. Data in each of the hydrochemical facies are combined to derive an average trend for each of the areas. Individual wells are also examined for temporal changes to show more localized variations. The locations of wells used to study the temporal changes are plotted on a map of the valley, and those wells showing significant changes are labeled with symbols indicating the direction of change (pl. 2).

Two variables are used in this study, dissolved-solids and nitrate concentrations. Dissolved solids measures the total amount of dissolved chemicals in a water, and it gives a general indication of overall water quality. Nitrate is derived from a number of potential pollution sources, such as fertilizers and sewage. Increases in nitrate would indicate specific influences of man's activities. These two variables will give a fairly comprehensive evaluation of any temporal changes that may be occurring.

METHODS OF DATA ANALYSIS

To determine the average changes occurring in a hydrochemical facies, some technique was needed so that wells with different average dissolved-solids or nitrate concentrations could be compared. This was accomplished by standardizing the data for each well to have a mean of zero and a standard deviation of one. Data from all the wells for each year could then be averaged with equal weight being given to each well. This data manipulation procedure produced a data set with one observation per year for the period of record in each hydrochemical facies. The yearly observations represented the average for all the wells for which data were available in each hydrochemical facies.

Trends in the chemistry of the facies were then studied using a linear regression of the standardized and averaged dissolved-solids or nitrate concentrations versus time. One of the fundamental assumptions of regression analysis is that the observations are independently distributed. For sequences of data collected over time, this requirement is sometimes violated because the data are autocorrelated. Because of memory effects in natural processes, measurements taken at one time may be correlated to measurements taken at previous times.

To test the extent to which the dissolved solids and nitrate data suffered from autocorrelation problems, lag one serial correlations were calculated, and cumulative frequency histograms of these autocorrelations compiled. Matalas, Slack, and Wallis (1975) have generated a series of empirical cumulative frequency histograms for data sequences having a range of serial correlations. By comparing the cumulative frequency histograms for dissolved solids and nitrate in the Sacramento Valley to these empirical histograms, the probable population autocorrelations were determined to be about 0.3 for dissolved solids and between 0.3 and 0.5 for nitrate.

Serial correlations of this magnitude indicate a tendency for subsequent values to be positively correlated to previous values. As a result, the trends determined from the regression analyses may not be as strong as indicated. Positive autocorrelations of this magnitude, however, will not significantly affect the conclusions of the temporal study.

The equations describing the average temporal changes for the hydrochemical facies were transformed back to concentrations by destandardizing the regression equations. For each hydrochemical facies, the average of the means and standard deviations of the individual wells was calculated. By multiplying the regression equations by these average standard deviations and adding the average means, equations were obtained that give the average trend in a facies in terms of concentrations. This equation describes what might be observed in a typical well in each facies, and no individual well can be expected to show the same relation.

The equations produced by this analysis are not predictive equations, but merely reflect the average rate of change over the period of record, from about 1955 to 1977. An example of the problems that can arise if they are used as predictive equations is demonstrated by considering what happens if some of the equations are used to estimate past concentrations. The equation describing the average changes in nitrate-nitrogen concentrations for the Victor Plain hydrochemical facies indicates negative concentrations in the ground water prior to 1939. This is a physical impossibility and arises because the equation was used for a purpose for which it was not intended. While predictions of future concentrations of dissolved solids and nitrate-nitrogen may not produce negative results, the values obtained could be just as meaningless.

In addition to testing for average trends throughout a hydrochemical facies, individual wells were examined for temporal variations. Where a significant trend was noted for an individual well, the equation was recorded and the well's location plotted on a map of the valley with a symbol indicating the direction of the trend (pl. 2).

Few wells in the valley have multiple observations over time. To minimize the effects of random fluctuations, only wells with seven or more observations for dissolved solids and six or more observations for nitrate were used. There was no attempt to assure a random distribution of wells throughout the valley, and all wells in the valley or along the margins having a sufficient number of observations were used. Time is measured as the year minus 1900. For example, for the year 1975, time is equal to 1975–1900 or 75.

DISSOLVED SOLIDS

Dissolved solids is a measure of the total amount of dissolved chemicals in water. An increase in any of the individual constituents will be reflected by an increase in the dissolved solids. While not many historical dissolved-solids measurements are available, many specific-conductance measurements have been made. Specific conductance is proportional to the quantity and valence of ionized chemicals in a water. Because almost all the major dissolved chemical constituents in a water are ionized, dissolved solids and specific conductance are closely related.

It was felt that dissolved solids would have more meaning for most users of this report; therefore, specific conductivities were transformed to dissolved-solids concentrations. The relation between dissolved solids and specific conductance will depend on the specific ionized species present and the amount of uncharged species, mainly silica, present in the water. For this reason, separate equations were derived for different parts of the valley. These areas do not exactly coincide with the hydrochemical facies as they were finally defined, but the division follows the same basic pattern. Thus, the effects of different water chemistries on the relation between dissolved solids and conductance were taken into account during the transformation.

Equations that describe the relation between dissolved solids and specific conductance were derived from a linear regression on data from about 650 wells having measurements of both dissolved solids and conductance. A linear equation with both slope and intercept terms was used rather than a ratio. The intercept terms of all the linear equations were significantly different from zero, which indicates that the linear equations better fit the data than ratios.

Because the calculation of dissolved solids from conductance is a simple linear transformation, the calculation in no way affects the presence of trends in the data. All dissolved-solids values for a well were estimated from conductance measurements even if some measured dissolved-solids concentrations were available. This prevented any changes that might be induced by using dissolved-solids data from different sources.

Locations of wells examined for trends in dissolved solids are shown on plate 2A. The changes for each hydrochemical facies are discussed in the next section and coefficients for the equations describing the average temporal changes are given in table 5. Coefficients for individual wells are summarized in table 6.

HYDROCHEMICAL FACIES

Dissolved solids in the Tuscan volcanic rocks hydrochemical facies show an average annual increase of 0.95 mg/L. The trend line accounts for 31 percent of the variation in the standardized dissolved-solids data averaged over all wells by year. A plot of the trend line is shown in figure 6. Temporal variations are significant in five of the 19 wells for which historical data are available (table 6). Two of these wells show rising trends and three show decreasing trends.

TABLE 5.—*Analyses of variance and coefficients for the regression of average yearly dissolved solids with time for the six hydrochemical facies in the Sacramento Valley*

[t=(year–1900); for example, t=(1980–1900)=80. NS, linear trend not significant at the 90 percent confidence level]

Hydrochemical facies	Number of wells	Source	Degrees of freedom	Sum of squares	F ratio	Probability of exceeding F ratio	r^2	MODEL Dissolved solids=A+Bt: A	90 percent confidence limit	B	90 percent confidence limit
Tuscan volcanic rocks	19	Model	1	1.52	8.89	0.01	0.31	194	±36	0.95	±0.55
		Error	20	3.43							
		Total	21	4.95							
Victor Plain	20	Model	1	2.50	13.91	<0.01	.38	236	±48	1.61	±0.74
		Error	23	4.13							
		Total	24	6.63							
Butte Basin	12	Model	1	1.17	12.55	<0.01	.41	197	±45	1.37	±0.67
		Error	18	1.68							
		Total	19	2.85							
Sutter Basin Basin	10	Model	1	.03	.05	.83	.00	---	---	NS	---
		Error	23	15.21							
		Total	24	15.24							
North alluvial fans	62	Model	1	1.05	14.11	<0.01	.43	222	±31	1.02	±.46
		Error	19	1.41							
		Total	20	2.46							
South alluvial fans	18	Model	1	7.41	65.16	<0.01	.76	184	±67	4.75	±1.01
		Error	21	2.39							
		Total	22	9.80							

TABLE 6.—*Wells showing significant trends in dissolved-solids concentration*

[For the model: Dissolved solids=A+Bt, where t is the year minus 1900]

Well	A	Standard error	Student's t	B	Standard error	Student's t	Probability of exceeding t for B
TUSCAN VOLCANIC ROCKS							
23N/01W-09L01M	-24.6	73.2	0.34	5.72	1.12	5.12	<0.01
25N/02W-16P01M	666.4	174.5	3.82	-6.09	2.42	2.52	.01
26N/02W-09E01M	909.5	257.0	3.54	-7.44	3.56	2.09	.04
27N/03W-15N01M	1055.6	288.1	3.66	-9.56	3.92	2.44	.02
27N/03W-22B01M	-122.4	223.1	.55	6.30	3.06	2.06	.04
VICTOR PLAIN							
06N/07E-23A01M	892.6	373.4	2.39	-10.32	5.61	1.84	0.07
18N/04E-28M01M	325.8	209.4	1.56	22.03	3.02	7.29	.01
BUTTE BASIN							
16N/04E-09D01M	-389.3	181.4	2.15	8.57	2.80	3.06	<0.01
17N/01W-30K03M	1833.2	515.4	3.56	-21.27	7.04	3.02	<0.01
SUTTER BASIN							
15N/03E-15H04M	-910.0	485.4	1.87	20.92	6.82	3.07	<0.01
16N/02W-25B02M	2428.1	395.1	6.15	-24.98	5.56	4.49	<0.01
NORTH ALLUVIAL FANS							
17N/03W-33R01M	383.2	76.6	5.01	3.24	1.13	2.87	<0.01
18N/02W-01E01M	-716.6	77.8	9.21	16.37	1.16	14.16	<0.01
18N/04W-02F01M	-817.1	112.5	7.26	22.73	1.74	13.07	<0.01
19N/02W-23N01M	-464.2	77.8	5.97	14.03	1.16	12.14	<0.01
20N/02W-22E01M	-618.4	442.7	1.40	11.31	5.97	1.89	.06
21N/02W-15C01M	-241.0	84.5	2.85	8.77	1.25	7.04	<0.01
21N/03W-02Q01M	-121.4	84.6	1.43	7.41	1.25	5.95	<0.01
22N/01W-29C01M	40.2	87.8	.46	3.98	1.30	3.06	<0.01
22N/02W-03A01M	125.3	77.8	1.61	3.37	1.16	2.91	<0.01
22N/02W-04C02M	-459.7	376.8	1.22	10.53	5.11	2.06	.04
22N/03W-06H01M	-922.3	553.3	1.67	20.71	7.62	2.72	<0.01
22N/03W-22Q01M	20.0	77.8	.26	3.88	1.16	3.35	<0.01
23N/03W-35B01M	-69.5	84.3	.82	3.40	1.25	2.73	<0.01
24N/03W-24P01M	-724.6	364.0	1.99	16.36	4.95	3.30	<0.01
25N/03W-31R01M	89.9	77.8	1.16	3.49	1.16	3.02	<0.01
SOUTH ALLUVIAL FANS							
06N/01E-19L02M	-661.9	209.8	3.15	18.11	3.15	5.76	<0.01
06N/01E-19Q01M	101.0	207.1	.49	5.94	3.05	1.95	.05
06N/01W-01B04M	-166.4	280.1	.59	7.48	4.04	1.85	.07
07N/02E-34C02M	-152.3	185.0	.82	10.56	2.81	3.75	<0.01
09N/04E-33L01M	-740.0	169.8	4.36	28.96	2.75	10.55	<0.01
13N/01W-07A01M	335.8	139.7	2.40	7.43	2.04	3.64	<0.01
13N/01W-36Q02M	-32.3	117.0	.28	4.67	1.74	2.68	<0.01
14N/03W-11H01M	7.9	166.3	.05	4.45	2.46	1.81	.07

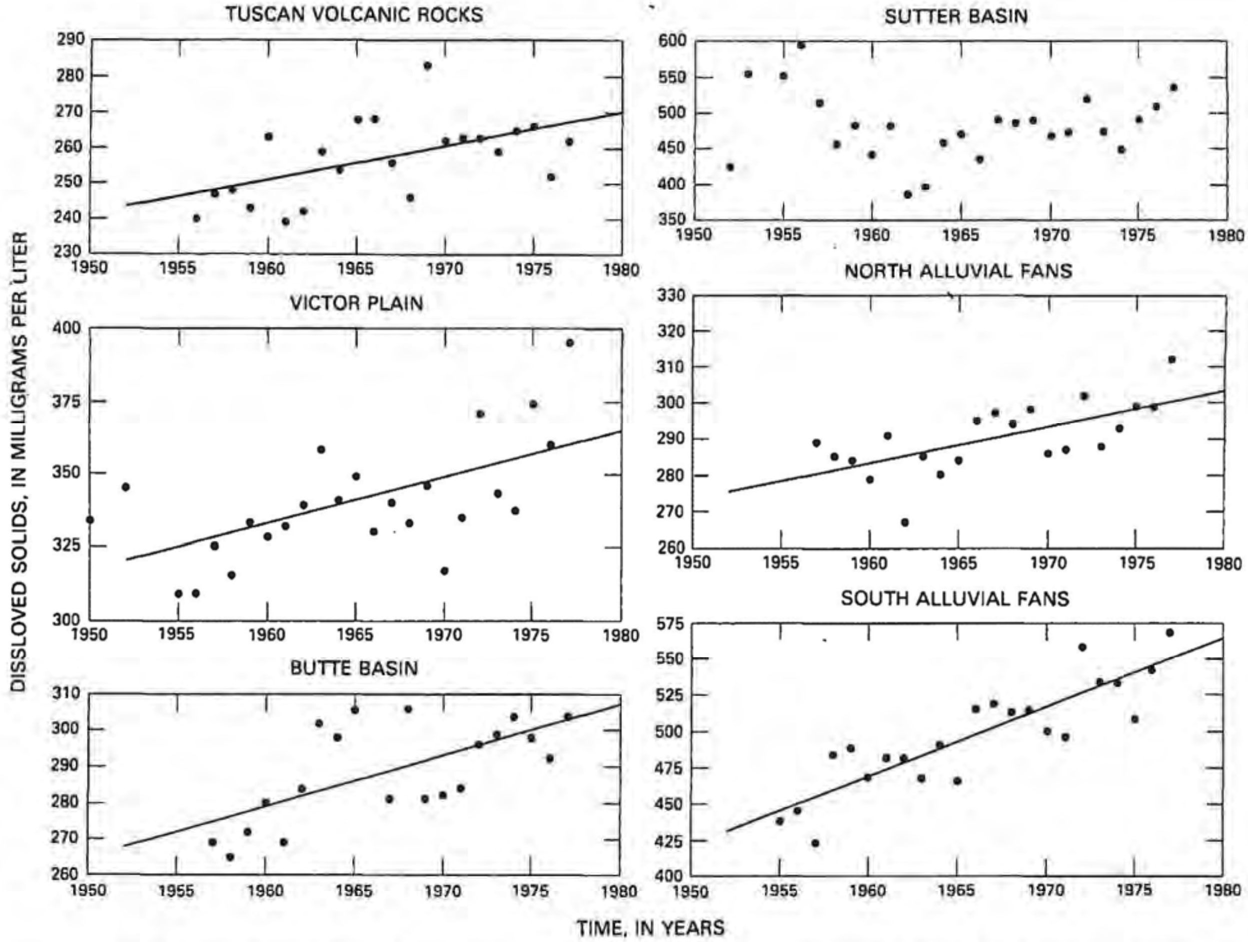

FIGURE 6.—Average yearly dissolved-solids concentrations versus time for the six hydrochemical facies in the Sacramento Valley. The coefficients and significance tests for the trend lines are given in table 5. If no line is shown, then the slope of the trend line is not significantly different from zero at the 90 percent confidence level. The technique by which the average yearly dissolved-solids values were derived is explained in the text.

The average yearly increase in dissolved solids for the Victor Plain facies is 1.61 mg/L. The trend line, which explains 38 percent of the variation in the standardized data, is shown in figure 6. Only two of the 20 wells studied in this facies showed significant changes, one of which showed an increase, and the other a decrease with time.

For Butte Basin, a temporal trend having a slope of 1.37 (mg/L)/yr explains 41 percent of the variation in the averaged data. In this facies also, two wells showed significant trends. One well demonstrated an increase and the other a decrease in dissolved solids with time.

Sutter Basin is the only hydrochemical facies to show no significant temporal change in average dissolved-solids concentration. Two of the 10 wells did show significant trends, but in opposite directions.

An increase in the average dissolved-solids concentration of the north alluvial fans facies of 1.02 (mg/L)/yr explains 43 percent of the variation in the yearly average data. A plot of the trend line is shown in figure 6. Of 62 wells that have seven or more observations in this area, 15 show significant upward trends, and none decrease.

Seventy-six percent of the variation in the average yearly dissolved-solids data are explained by a linear trend in the south alluvial fans facies. The slope is very steep 4.75 (mg/L)/yr and indicates a very rapid increase in dissolved solids (fig. 6). Of the 18 wells examined in this facies, 8 had significant increases in dissolved solids. There were no wells that showed decreases.

NITRATE

A certain amount of nitrate is present in precipitation, and chemical reactions in the soil zone may add to this amount. Thus, even under natural conditions, a finite amount of nitrate will exist in ground water. An estimate of natural nitrate concentrations in the Sacramento Valley can be made from data gathered during the period 1912–13 (Bryan, 1923). The median nitrate-nitrogen concentration in these 43 samples is 0.67 mg/L. The highest nitrate-nitrogen concentration measured was 14 mg/L, which suggests some wells were polluted as long as 70 years ago. From the frequency histogram of the 1912–13 nitrate data (fig. 7), it is estimated that under natural conditions, no more than about 3 mg/L nitrate-nitrogen would be expected in the ground water.

By the period 1974–78, the median nitrate-nitrogen concentration had more than doubled to 1.6 mg/L. The maximum observed nitrate-nitrogen concentration also increased, with two wells containing 27 mg/L and one well 61 mg/L. These increases likely reflect the influences of man's activities, and the extent of temporal changes was, therefore, investigated to determine the magnitude of the problem.

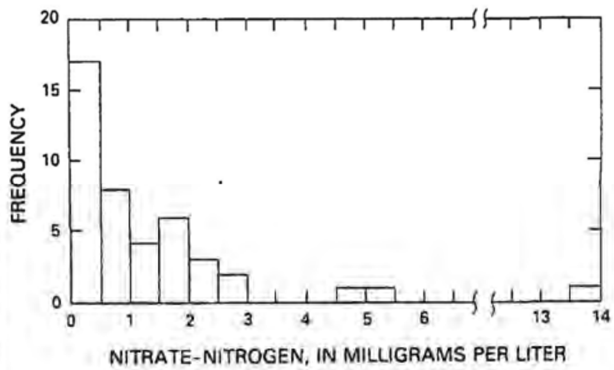

FIGURE 7.—Frequency histogram of dissolved nitrate-nitrogen concentrations in wells, 1912–13. Data from Bryan (1923).

Locations of wells examined for trends in nitrate are shown on plate 2*B*. The changes for each hydrochemical facies are discussed further and coefficients for the equations describing the average temporal changes are given in table 7. Coefficients for individual wells are summarized in table 8.

TABLE 7.—*Analyses of variance and coefficients for the regression of average yearly nitrate-nitrogen concentrations with time for the six hydrochemical facies in the Sacramento Valley*

[t=(year–1900); for example, t=(1980–1900)=80. NS, linear trend not significant at the 90 percent confidence level]

								MODEL Nitrate nitrogen=A+Bt			
Hydrochemical facies	Number of wells	Source	Degrees of freedom	Sum of squares	*F* ratio	Probability of exceeding *F* ratio	r^2	A	90 percent confidence limit	B	90 percent confidence limit
Tuscan volcanic rocks	5	Model Error Total	1 15 16	0.88 10.57 11.45	1.25	0.28	0.08	---	---	NS	---
Victor Plain	13	Model Error Total	1 17 18	6.05 3.51 9.56	29.31	<0.01	.63	-1.402	±0.751	0.036	±0.012
Butte Basin	3	Model Error Total	1 14 15	.69 5.26 5.95	1.85	.20	.12	---	---	NS	---
Sutter Basin	2	Model Error Total	1 10 11	.65 7.77 8.42	.84	.38	.08	---	---	NS	---
North alluvial fans	26	Model Error Total	1 18 19	5.02 1.82 6.84	49.67	<0.01	.73	-3.786	±1.625	.099	±0.024
South alluvial fans	13	Model Error Total	1 18 19	2.03 4.73 6.76	7.72	.01	.30	-0.506	±1.514	.036	±0.023

TABLE 8.—*Wells showing significant trends in nitrate-nitrogen concentration*

[For the model: Nitrate-nitrogen=A+Bt, where t is the year minus 1900]

Well	A	Standard error	Student's *t*	B	Standard error	Student's *t*	Probability of exceeding *t* for B
TUSCAN VOLCANIC ROCKS							
23N/01W–09L01M	–25.33	3.82	6.63	0.53	0.06	8.78	<0.01
25N/02W–07K01M	–7.96	3.74	2.13	.17	.06	2.89	<0.01
VICTOR PLAIN							
10N/05E–06M02M	–6.58	1.62	4.06	0.12	0.03	4.85	<0.01
11N/06E–16M01M	–9.38	1.35	6.96	.18	.02	8.56	<0.01
13N/05E–13D01M	–3.98	2.09	1.90	.08	.03	2.31	.02
14N/05E–32R03M	–14.48	2.19	6.60	.23	.03	7.38	<0.01
18N/04E–07A01M	–0.81	1.09	.75	.03	.02	1.87	.06
BUTTE BASIN							
None							
SUTTER BASIN							
None							
NORTH ALLUVIAL FANS							
18N/04W–02F01M	–73.57	6.37	11.54	1.38	0.10	13.96	<0.01
20N/03W–02D01M	–11.39	7.49	1.52	.23	.12	1.95	.05
21N/02W–15C01M	–15.47	5.62	2.75	.29	.08	3.43	<0.01
21N/03W–02Q01M	–33.53	7.80	4.30	.58	.12	4.89	<0.01
22N/01W–29C01M	–8.35	6.41	1.30	.17	.10	1.70	.09
22N/02W–03A01M	–10.26	6.16	1.67	.28	.10	2.92	<0.01
25N/03W–31R01M	–10.34	6.88	1.50	.24	.10	2.30	.02
SOUTH ALLUVIAL FANS							
09N/02E–10D01M	26.38	6.93	3.81	–0.38	0.11	3.44	<0.01
13N/01W–07A01M	–10.19	2.66	3.84	.21	.04	5.26	<.01
13N/01W–08B01M	–11.80	2.36	5.00	.22	.04	6.13	<.01
14N/03W–11H01M	–4.40	2.75	1.60	.10	.04	2.33	.02
14N/03W–14Q02M	–25.22	5.95	4.24	.38	.08	4.55	<.01

HYDROCHEMICAL FACIES

No significant average trend was found for the Tuscan volcanic rocks hydrochemical facies. However, two of the five wells examined did show significant upward trends in nitrate concentrations.

A linear trend with a slope of 0.036 (mg/L)/yr explains 63 percent of the temporal variation in the average yearly nitrate-nitrogen concentrations in the Victor Plain facies. A plot of this trend line is shown in figure 8. Of 13 wells in this area that had 6 or more observations, 5 showed significiant upward trends. None of the wells showed a significant decrease.

Neither Butte nor Sutter Basin had a significant average trend in nitrate. Also, there were no individual wells in either that showed any significant changes. However, with only three wells in Butte Basin and two in Sutter Basin having six or more observations, there are too few samples for the results of the test to be conclusive.

The nitrate-nitrogen concentrations in the north alluvial fans hydrochemical facies show a distinct upwards

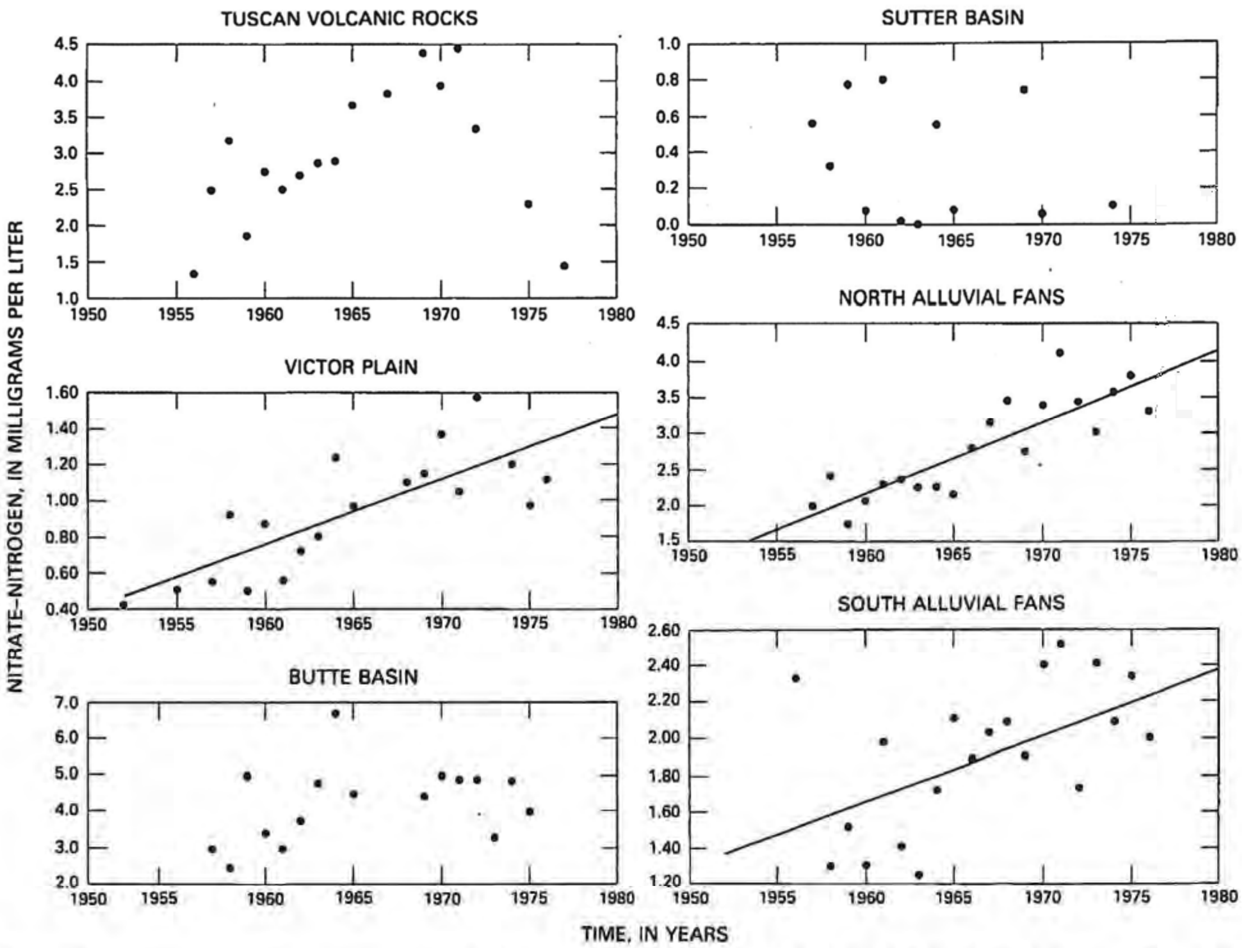

FIGURE 8.—Average yearly nitrate-nitrogen concentrations versus time for the six hydrochemical facies in the Sacramento Valley. The coefficients and significance tests for the trend lines are given in table 7. If no line is shown, then the slope of the trend line is not significantly different from zero at the 90 percent confidence level. The technique by which the average yearly nitrate-nitrogen values were derived is explained in the text.

trend with a slope of 0.099 (mg/L)/yr. Seven of the 26 wells in this facies showed significant upwards trends. The plot of the trend in figure 8 shows that the average concentration of nitrate-nitrogen in this facies has exceeded 3.0 mg/L, the maximum expected under natural conditions.

For the south alluvial fans hydrochemical facies, a linear trend having a slope of 0.036 (mg/L)/yr explains 30 percent of the temporal variation in the average annual nitrate-nitrogen concentrations. Thirteen wells had six or more observations over time, and 5 of them show significant temporal changes. Four have upwards trends, and 1 a downwards trend.

HYPOTHESIS TESTING

Because trends in the data for the individual wells were tested at the 90 percent confidence level, there is a 10 percent chance that no significant trend exists in the valley. The significant slopes that were observed could result from normally distributed random fluctuations about a true true slope of zero. If this were the case, 5 percent of the wells could show a significant increase, and 5 percent a significant decrease, although no real trend existed. If more than 5 percent of the dissolved-solids or nitrate wells show significant trends in the same direction, then it can be concluded that there has been a significant change for that species.

Of 140 wells in the Sacramento Valley tested for trends in dissolved solids, 28 (20 percent) showed an increase and 7 (5 percent) showed a decrease with time. Under the null hypothesis that no change in dissolved solids is occurring at the 90 percent confidence level, it would be expected that by random variation, 7 of the wells would show a significant decrease and 7 would show a significant increase. For dissolved solids, the number of wells showing increases exceeds the number expected by random variation, and the increase in dissolved solids is significant.

Of 62 wells tested for trends in nitrate, 18 (29 percent) showed increases, but only 1 (2 percent) showed a decrease with time. Under the null hypothesis of no change, 3 can be expected to increase and 3 to decrease by random variation at the 90 percent confidence level. Because 29 percent of the wells showed significant increases in nitrate, the null hypothesis can be rejected, which indicates significant increases in nitrate are occurring in the Sacramento Valley.

PROCESSES CONTROLLING GROUND-WATER CHEMISTRY

Differences in the chemical composition of ground water among the six hydrochemical facies in the Sacramento Valley indicate that either different processes control the water chemistry in different areas, or that there are spatial variations in the same process. In this section, the major controlling processes are delineated from the chemical data using principal components analysis. Factor scores are than calculated for each well that reflect the magnitude of each component in that well. By studying the spatial trends in the factor scores using trend surface analysis, the areal variations in processes can be determined. Contour maps of these surfaces show the spatial distributions of the more important processes controlling ground-water chemistry.

METHODS OF DATA ANALYSIS

PRINCIPAL COMPONENTS ANALYSIS

Principal components analysis (Rummel, 1970; Davis, 1973) is used to separate the variance of a data matrix into common and unique components. Variables, in this case dissolved chemical species, that are controlled by the same process will share a common variance structure. Principal components analysis will group the variables on the basis of this shared variation and will calculate a correlation between variables and components. These components represent independent sources of variation in a data matrix and can be interpreted in terms of controlling processes using knowledge of geochemical principles.

From the correlations, or loadings as they are termed, between variables and components, factor scores can be calculated for each well that measure the intensity of a component in that well. These factor scores are a composite of all the chemical species that load on a component and summarize similar behavior in a number of different species. Where several of the chemical species are controlled by the same process, this transformation to factor scores reduces the number of variables needed to account for the significant variation in the data. The factor scores can be further analyzed as any other numerical variable.

TREND SURFACE ANALYSIS

Trend surface analysis (Davis, 1973) is a technique for separating variation in geographically distributed data into regional and local parts. Either of these parts might be the goal of a particular study. For the distribution of processes in the Sacramento Valley, however, the regional variation is of interest. A trend surface is delineated by a polynomial equation that predicts the magnitude of some variable in terms of the geographic coordinates of a set of observations. The criteria for fitting the polynomial is to minimize the squared deviations about the surface. In this study, the trend surface represents the spatial variation in processes controlling ground-water chemistry. By contouring the surface, maps can be prepared that show the spatial variation in the magnitude of the process.

PROCESSES AND THEIR SPATIAL VARIATION

For the Sacramento Valley, 15 variables (table 9) were included in the principal components analysis. A major assumption of components analysis is that the data are normally distributed. This requirement was reasonably well met by using logarithmic transformations of the chemical concentrations. Four principal components explained 73 percent of the total variation in the data and accounted for all the significant common variation (that is, only these four components had eigenvalues greater than one). The four individual components explained 36, 17, 11, and 9 percent of the total variation. Because neither the third nor fourth component yielded clear interpretations that could be attributed to processes, only the first two components are presented. These two components, however, explain

TABLE 9.—*Chemical variables included in the principal components analysis of the Sacramento Valley*

Dissolved solids	Potassium	Silica	Nitrate
Calcium	Manganese	Bicarbonate	Phosphate
Magnesium	Arsenic	Sulfate	Fluoride
Sodium	Boron	Chloride	

TABLE 10.—*Results of principal components analysis on chemical data from the Sacramento Valley*

[All loadings with absolute values less than 0.30 have been omitted for clarity]

	Components 1	Components 2	Communalities
Dissolved solids	0.94		0.93
Calcium	.76		.60
Magnesium	.81		.67
Sodium	.83		.76
Bicarbonate	.85		.72
Chloride	.76		.62
Sulfate	.63		.41
Boron	.65		.42
Fluoride	.30	−0.46	.30
Silica	−0.54	.42	.46
Potassium		.67	.48
Nitrate		−0.71	.52
Phosphate		.50	.30
Manganese		.63	.41
Arsenic		.62	.38
Percent variation explained	36	17	
Cumulative percent variation explained	36	53	

over 50 percent of the variation in the chemical data from the Sacramento Valley.

Table 10 shows the results of the principal components analysis. On component one, dissolved solids, calcium, magnesium, sodium, bicarbonate, chloride, sulfate, boron, and fluoride all have positive loadings. Silica is the only species to have a significant negative loading on this component. The inverse loadings of dissolved solids and silica indicate that low silica concentrations tend to be found in conjunction with high dissolved-solids concentrations, and vice versa. The positive loadings of all the major chemical species on this factor indicate a source high in calcium, magnesium, sodium, bicarbonate, chloride, and sulfate. This source is also high in fluoride and boron, and low in silica.

The trend surface map of this component (fig. 9) shows a distinct linear trend across the valley, which accounts for 36 percent of the spatial variation in component one. Low values of component one along the eastern margin and in the northern end of the valley indicate low dissolved-solids and high silica concentrations. In the southwestern corner, high concentrations of dissolved species and boron are indicated. This distribution in the ground water is very similar to the distribution of water chemistry in surface streams draining into the valley. Table 11 shows the average concentrations of dissolved species in streams entering the valley from certain areas. East side streams are low in dissolved solids, and contain twice as much silica as streams from the southwestern margin. The silica in east side streams is likely from the weathering of volcanic detritus in the Sierra Nevada and Cascade Range. High dissolved-solids concentrations in the southwest originate in thermal springs in the Coast Ranges.

The first principal component represents the effects of the chemistry of recharge to the valley on the chemistry of the ground water. This process is active along both margins of the valley and produces fairly uniform chemical compositions along the eastern side. Along the western margin, changes in surface-water chemistry from north to south induce changes in ground-water chemistry. The effects of recharge chemistry are the single most important control on ground-water chemistry, accounting for over one-third of the total variation in the chemical data.

The second principal component (table 10) explains 17 percent of the variation in the chemical data, and contains positive loadings of silica, potassium, phosphate, manganese, and arsenic. Nitrate and fluoride have negative loadings on this component. The trend surface for component two (fig. 10) explains 38 percent of the spatial variation in this component. The pattern indicates high factor scores in the center of the valley with low values along the margins. The occurrence of high factor scores in wells in the flood basins suggests that the fine-grained sediments and reducing conditions in the basins are an important control on water chemistry.

Measurements of dissolved oxygen in the ground water in the south alluvial fans facies (table 12) show an average of 3.8 mg/L of dissolved oxygen. Although no data are available for other parts of the valley, it is reasonable to assume that the coarse-grained sediments along the valley margins would contain some dissolved oxygen. In the flood basins, where sediments are water saturated and fine grained, reducing conditions probably exist. The increase in manganese and arsenic, and decrease in nitrate, support an oxidation-reduction effect. The solubility of manganese and arsenic increases in reducing conditions, and nitrate could be removed by denitrification.

Longer residence times in the fine-grained sediments of the flood basins and weathering of volcanic detritus from Sutter Buttes could supply the higher silica and potassium concentrations indicated by component two. The inverse relation between phosphate and fluoride probably reflects spatial differences in their sources rather than equilibrium with a mineral phase, such as apatite. Phosphate, introduced along with nitrate, would not be removed by reduction reactions and would persist in the ground water. Fluoride is probably derived from thermal springs in the hills surrounding the valley and lacks a source in the central basins.

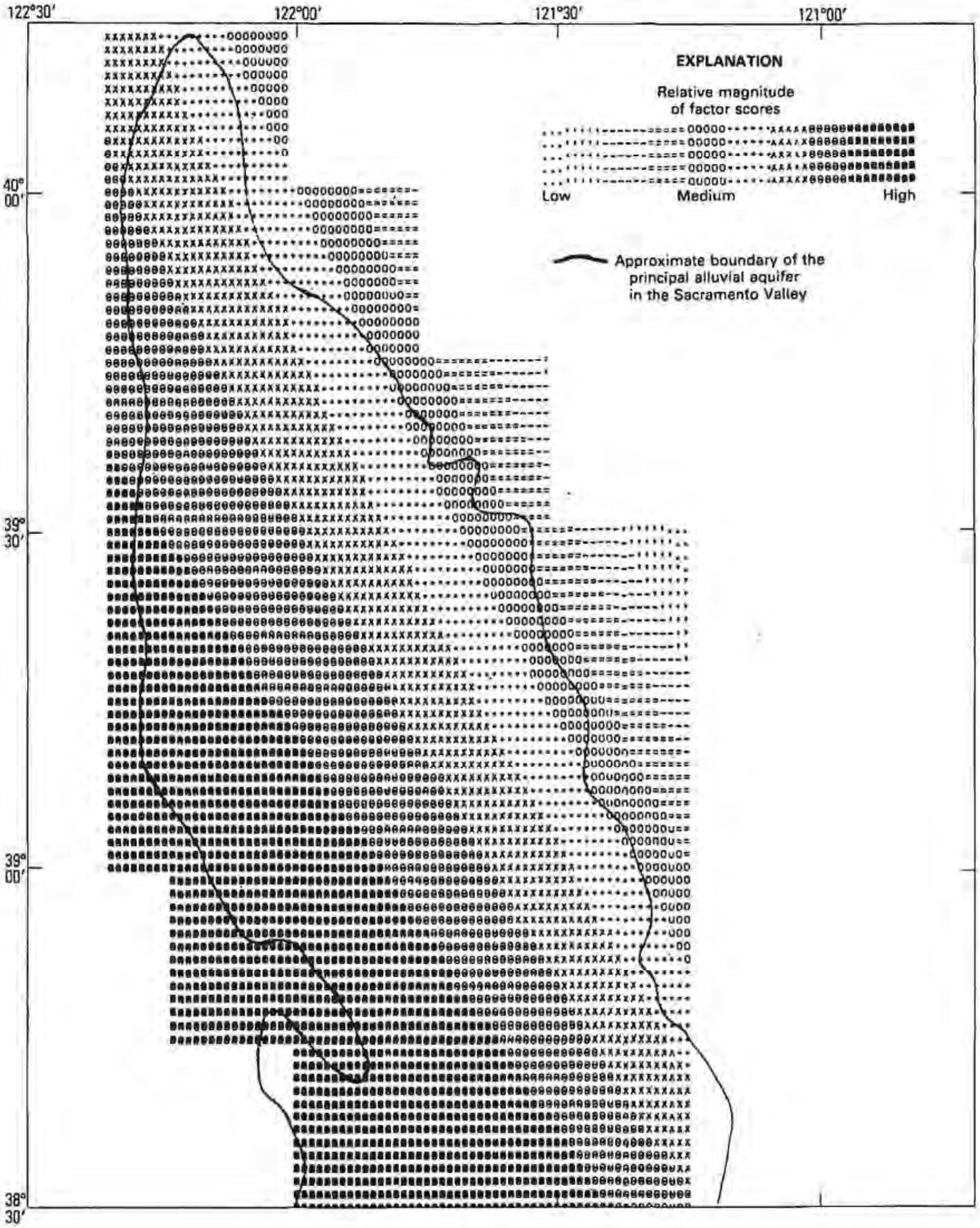

FIGURE 9.—Trend surface of factor scores for component one.

Principal components analysis shows that two components account for over 50 percent of the variation in the chemical data from the Sacramento Valley. While other processes will affect water chemistry, they seem to be either more localized or much less important than the two discussed. Recharge from the valley margins

TABLE 11.—*Average chemical compositions of surface water entering the Sacramento Valley*

Species (mg/L)	East side	Northern west side	Southern west side
Dissolved solids	85	215	592
Calcium	11	36	53
Magnesium	4.7	12	40
Sodium	6.3	13	101
Bicarbonate	55	164	314
Chloride	5.4	16	150
Sulfate	7.0	28	82
Boron	.10	.07	.51
Fluoride	.08	.08	.4
Silica	22	14	11

EXPLANATION OF LOCALITIES

East side: Antelope Creek, Mill Creek, Big Chico Creek, Butte Creek, Feather River, Yuba River, Bear River, and American River.
Northern west side: Red Bank Creek, Elder Creek, Thomes Creek, and Stony Creek.
Southern west side: Stone Corral Creek, Lurline Creek, Freshwater Creek, Salt Creek (west of Williams), Cortina Creek, Sand Creek, Oat Creek, Cache Creek, and Putah Creek.

is the most important control on ground-water chemistry, with reactions in the flood basin sediments also being important.

MINERAL STABILITY RELATIONS

Sediments deposited in the Sacramento Valley have been derived from erosion of the surrounding mountains. These mountains contain igneous and metamorphic rocks which were formed at higher temperatures and (or) pressures than are found at shallow depths in the valley sediments. Because the environment of deposition is radically different from that of formation, these minerals are generally not in equilibrium with their surroundings. As a result, the minerals react with the ground water, which dissolves the unstable primary minerals and forms secondary minerals that are more stable. Reaction rates may be very slow, so the process is gradual and can take tens of millions of years or longer. During this diagenesis, phases, such as pyroxenes, feldspars, micas, and volcanic glass, weather to more stable phases, such as clay minerals and iron hydroxides.

Water chemistry will be affected by water-rock interactions, and the three parts of the system (primary minerals, aqueous solution, and secondary minerals) are interdependent. Using thermodynamic calculations, the mineral phases that will be stable in equilibrium with solutions of various compositions can be predicted. It cannot be justifiably presumed, however, that the mineral assemblage and the ground-water chemistry are in thermodynamic equilibrium, particularly where aluminosilicate minerals are involved. Water chemistry may reflect incomplete reactions or partial equilibrium with metastable phases.

In this section, the relations between water chemistry and aquifer mineralogy are examined. Mineralogy is presented from two U.S. Geological Survey test wells. Mineral saturation indices are examined to determine any likely phases that may be controlling water chemistry. Finally, stability and metastability fields of mineral phases are compared to measured water chemistry to determine what secondary minerals will be most stable in contact with Sacramento Valley ground water.

MINERALOGY OF SEDIMENTS

Sidewall samples were collected from various depths in two test wells drilled by the U.S. Geological Survey during 1979. Data from two wells do not provide a comprehensive evaluation of sediment mineralogy, but they do provide a partial guide to what minerals may be present. Not all the samples have been analyzed as of the time of this writing and additional mineralogic data will be published in the future as basic data reports.

WELL 12N/01E–34Q

The mineralogy of sidewall samples from well 12N/01E–34Q was determined by optical microscope identification of the 0.5- to 0.125-mm size fraction. Table 13 shows the percent compositions of minerals, in this size range, for five samples collected from 323 feet to 897 feet. Data from an additional sample at 1,845 feet is also given. Feldspars compose an average of about two-thirds of the mineral grains, with about one-fifth being quartz and one-tenth being rock fragments. In all the shallower samples, the percent plagioclase having an anorthite content greater than 34 percent is smaller in the fine fraction than in the medium. The sample from 1,845 feet has an unusually small amount of anorthite-rich plagioclase in the medium fraction. The albitic plagioclase component increases between medium and fine fractions in all but one sample. The smaller size fractions, which are chemically more reactive, are dominated by albitic plagioclase.

Lithic fragments from a gravel at 1,856 feet, having a distinct greenish hue, were examined by X-ray diffraction. The sample near this depth was unusually rich in heavy lithic fragments (table 13). X-ray analysis of these fragments indicates that the composition is quartz, plagioclase, and chlorite (Ivan Barnes, U.S. Geological Survey, personal commun., 1979). The mineralogy of the sediments determined by optical methods may not reflect the complete mineralogy, especially where some minerals are contained in rock fragments which are not differentiated mineralogically. Mineral phases identified in samples from this well are shown in table 14.

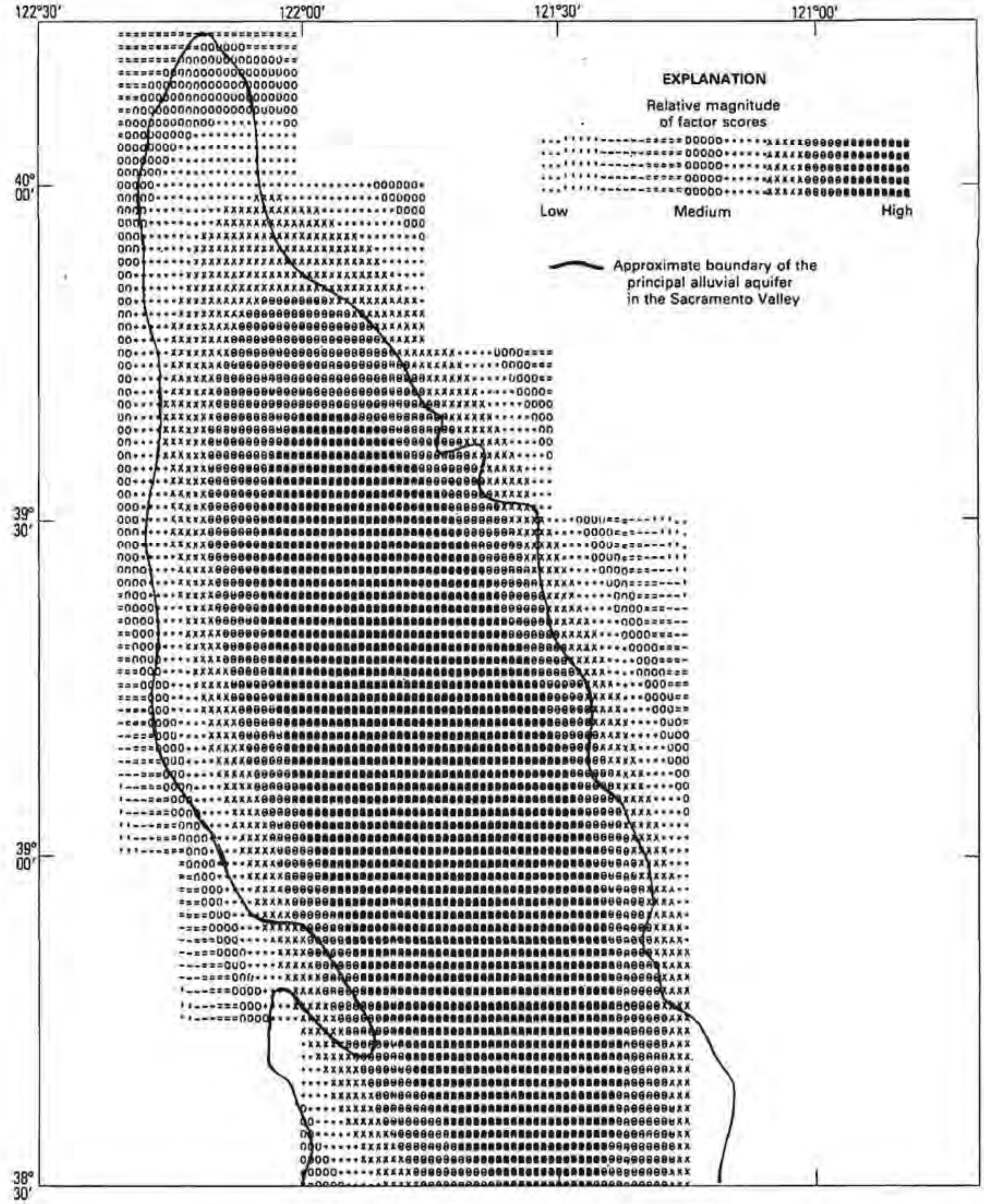

FIGURE 10.—Trend surface of factor scores for component two.

WELL 19N/01W–32G

The mineralogy of a number of fine-grained layers was determined by X-ray diffraction analysis of sidewall samples from well 19N/01W–32G. The results of the analyses are shown in table 15. Below a depth of about 562 feet, a large component of X-ray amorphous material is present in the sediments. Whether this is primary volcanic glass or an intermediate weathering

TABLE 12.—*Dissolved-oxygen concentrations in well water in the south alluvial fans facies*

Well	Date	Dissolved oxygen (mg/L)
08N/03E–05N04M	08–01–79	1.9
08N/03E–06M01M	08–01–79	2.0
08N/01E–06B01M	07–31–79	5.9
08N/01E–17C01M	07–26–79	5.0
09N/03E–31L01M	08–01–79	2.0
09N/02E–18N01M	07–31–79	4.4
09N/02E–33E01M	07–31–79	7.8
09N/01E–35H02M	07–31–79	3.8
09N/01W–25M01M	07–31–79	3.2
10N/02E–03E01M	07–25–79	2.8
11N/01W–01D01M	07–25–79	3.5
Mean		3.8

product, such as an amorphous aluminosilicate (Paces, 1978) was not investigated. The two clay minerals present in quantity are halloysite and illite. The presence of halloysite rather than kaolinite was determined using transmission electron microscopy. Figure 11 shows an electron micrograph of sediments from the 407-foot depth. The tubular structures at the center and top of the figure are halloysite, with poorly formed flakes of illite also visible. The dark, blocky particles are fine-grained quartz and plagioclase.

Optical examination of sand-size grains shows that the mineralogy is consistent with an andesitic sand. The major mineral is plagioclase, which is zoned and shows etching. Some pyroxenes are present and are clear to light green. Many of the grains are stained by ferric hydroxides.

SATURATION INDICES

According to the law of mass action, when an aqueous solution is in equilibrium with a mineral, the ion-activity product for that mineral will equal the thermodynamic equilibrium constant. The degree of saturation of a water can be represented by the saturation index (*SI*), which is the logarithm of the quotient of the ion-activity product (*IAP*) divided by the equilibrium constant (*K*):

$$SI = \text{Log}\,\frac{IAP}{K}, \tag{1}$$

where

SI=saturation index

IAP=ion-activity product, and

K=thermodynamic equilibrium constant.

The saturation index has a value of zero when the solution is in equilibrium with a solid phase. A positive saturation index indicates supersaturation and a negative index undersaturation with respect to some mineral. Minerals that are present in an aquifer and have negative saturation indices can dissolve. Minerals that have positive saturation indices may precipitate from solution, although whether this actually occurs depends on additional factors. By examining the saturation indices of water samples collected from the Sacramento Valley, some idea can be obtained about which minerals may be influencing ground-water chemistry.

TABLE 13.—*Mineralogic compositions of sidewall samples from U.S. Geological Survey test well 12N/01E–34Q*

c—coarse >0.5 mm.
m—medium 0.5–0.25 mm.
f—fine 0.25–0.125 mm.
vf—very fine 0.125–0.0625 mm.
p—pan <0.0625 mm.

VAB—very abundant, from 25–50 percent of the heavy minerals.
AB—abundant, from 10–25 percent of the heavy minerals.
SP—sparse, from 1–4 percent of the heavy minerals.

Sample depth, in feet	323		467		685		788		897		1845	
Texture, in percent c/m/f/vf/p	7/2/41/34/17		2/2/8/43/45		3/5/19/38/36		60/22/10/3/5		8/52/28/4/8		59/18/6/4/12	
Size interval	m	f	m	f	m	f	m	f	m	f	m	f
Composition, in percent:												
Potassium feldspar	12	13	6	16	27	13	15	14	15	12	10	12
Plagioclase (Anorthite<34)	25	44	40	33	22	32	21	36	28	39	19	24
Plagioclase (Anorthite>34)	28	10	24	14	25	16	23	12	23	14	3	13
Quartz	20	23	20	28	20	26	21	18	7	13	31	18
Lithic fragments	11	10	7	6	4	10	14	13	21	12	21	11
Heavy minerals[1]	3	1	3	3	2	2	5	6	6	13	15	23
Nonopaque heavy grains:												
Sausserite	VAB		VAB		VAB		VAB		AB		AB	
Uralite	VAB		VAB		VAB		VAB		AB		AB	
Goethite	VAB		VAB		VAB		VAB		AB		AB	
Lithic fragments	AB		SP		SP		AB		AB		VAB	

[1]Heavy minerals have specific gravities greater than 2.9.

TABLE 14.—*Minerals identified in sidewall samples from U.S. Geological Survey test well 12N/01E–34Q, in alphabetical order*

Actinolite-tremolite (series)[1]	Glaucophane
Amphiboles	Graphite
Analcite	Hematite (some specular)
Apatite	Hercynite
Augite-ferroaugite (series)[1]	Hornblende (green, brown, and oxy-varieties)
Basic glass	Hypersthene
Biotite	Lawsonite
Bronzite-ferrohypersthene (series)[1]	Marcasite
Chlorite	Pigeonite
Chromite	Plagioclase (series)[1]
Chrysotile	Potash feldspar (undifferentiated)
Clinozoisite	Pumpellyite
Cordierite	Richterite (part of series)[1]
Cummingtonite	Riebeckite
Diopside-hedenbergite (series)[1]	Serpentine (?)
Enstatite-bronzite (series)[1]	Sideromelane
Epidote	Sphene (titanite)
Fluorite	Spinel
Garnet (red)	Staurolite
Glauconite	Zircon
	Zoisite

[1]"Series" means several varieties within the series were found.

TABLE 15.—*Percent mineral composition of sidewall samples from U.S. Geological Survey test well 19N/01W–32G*
[Tr, trace; unid., unidentified; inter., intermediate; ND, not detected]

Depth (feet)	Quartz	Plagioclase	Amorphous	Halloysite	Illite	Other
260	35–45	25–35	ND	15–20	5–10	Tr unid.
353	40	15–20	ND	10–15	ND	Tr minor.
407	35–40	20–25	ND	10–15	2–5	Tr minor.
478	35–40	25–30	ND	10–15	5–10	5-10 Chlorite.
562	10–20	15–25	Major	5–15	2–5	ND.
630	20–25	15–20	Inter.	5–10	2–10	Tr unid.
930	15–20	10–15	Inter.	10–15	5–10	ND.
984	5–15	5–10	Major	10–15	1–5	Tr unid.
1,098	5–10	5–10	Major	5–10	1–5	ND.
1,193	5–15	5–10	Major	5–10	1–5	Tr minor.
1,390	5–10	2–5	Major	2–5	2–5	ND.

Saturation indices were calculated for 271 water analyses selected from those published by Fogelman (1975, 1976) and Fogelman and Rockwell (1977). Of the 271, 153 had aluminum analyses and 183 had iron analyses. Temperature, pH, and alkalinity were determined in the field. Samples for cation determinations were passed through a 0.1-micrometer filter and acidified with concentrated nitric acid. Some controversy exists as to the validity of aluminum and iron data gathered in this manner; however, the possible error introduced is generally small (Kennedy and others, 1974; Barnes, 1975). Some of the supersaturation in the aluminosilicate and iron minerals may be due to particulate iron and aluminum passing through the filter. Saturation indices were calculated using WATEQF (Plummer, and others, 1978).

Table 16 shows the mean, minimum, and maximum saturation indices for selected mineral phases along with log equilibrium constants at 20°C, the average temperature of ground waters in the Sacramento Valley. Although many minerals, such as the feldspars and montmorillonite, show variations in chemical composition, saturation indices were calculated for ideal mineral phases. Therefore, stability calculations for these minerals only approximate actual conditions, but they do provide useful indicators of the types of reactions that may be occurring.

Most waters are close to saturation with respect to silicaglass, as might be expected from the volcanic detritus in the sediments. All samples were supersaturated with respect to amorphous ferric hydroxide, which may reflect the variability in solubility with particle size or particulate iron passing through the 0.1-micrometer filter during sampling. The waters tend to be at saturation with respect to gibbsite and slightly below saturation with respect to amorphous aluminum hydroxide.

Ground water is fairly close to saturation with respect to the carbonate minerals, calcite, dolomite, and magnesite. No carbonate minerals were recorded in sediments from either of the wells examined for mineralogy. Apparently, the formation of secondary carbonate minerals is of limited extent despite a number of samples indicating supersaturation with respect to calcite.

Potassium and sodium feldspars, which are abundant in the sediments, average close to saturation in Sacramento Valley ground water. Dissolution of these phases probably contributes to water chemistry where ground water is undersaturated with respect to these feldspars. All water samples are undersaturated with respect to anorthite, which is less abundant in the sediments. Halloysite is the only clay mineral with which the ground water is not supersaturated. Any of the other clay minerals could potentially form from most of the waters. When stability fields are considered, however, only one phase will be the most stable. These phase relations can be illustrated using activity diagrams.

ACTIVITY DIAGRAMS

Activity diagrams can be used to illustrate the phase relations among primary and secondary minerals and to predict the most stable secondary phases as a function of water chemistry. Such diagrams have been used by Feth, Roberson, and Polzer (1964), Tardy (1971) and White (1979) to depict weathering reactions in ground

FIGURE 11.—Electron micrograph of sediments from the 407-foot depth of well 19N/01W–32G. (Photograph by Technology of Materials, Santa Barbara, Calif.)

waters. The technique for calculating such diagrams is given in Garrels and Christ (1965), and Helgeson, Brown, and Leeper (1969) give numerous examples of such diagrams. A slightly different type of diagram, though basically similar, was presented by Kittrick (1969), and it depicts equilibrium between solid phases and an aqueous solution.

As an example of the calculation of the equilibrium boundary between two phases, the calculation of the phase boundary between illite and montmorillonite is given below. Formulas for these minerals are taken from WATEQF (Plummer, and others, 1978). For the reaction illite ⇆ montmorillonite, the chemical equation is written

TABLE 16.—*Mean, minimum, and maximum saturation indices in Sacramento Valley ground water for selected mineral phases*

Phase[1]	n	[2]Log K at 20 °C	Saturation index		
			Mean	Minimum	Maximum
Silica glass	271	-3.07	-0.14	-0.58	0.16
$Fe(OH)_3$ amorph.	183	4.885	1.31	.62	3.67
$Al(OH)_3$ amorph.	153	-31.77	-1.13	-2.32	.03
Gibbsite	153	-32.95	.05	-1.16	1.22
Fluorite	269	-11.02	-2.38	-3.50	-0.10
Hydroxyapatite	270	-59.57	-2.22	-7.57	1.64
Strengite	183	-26.37	-0.61	-2.06	1.05
Calcite	271	-8.45	-0.33	-1.80	.50
Dolomite	271	-16.92	-0.54	-3.37	1.24
Magnesite	271	-8.16	-0.53	-1.96	.43
Adularia	153	-20.96	.22	-1.81	1.66
Albite	153	-18.32	-0.82	-2.93	.47
Anorthite	153	-19.55	-3.27	-5.95	-1.77
Halloysite	153	-33.38	-0.89	-3.76	1.38
Kaolinite	153	-37.52	3.26	.32	5.58
Illite	153	-40.99	2.31	-1.33	4.53
Montmorillonites:					
1. Calcium	153	-45.73	3.40	-0.37	5.84
2. Belle Fouche.	95	[3]-34.97	7.49	4.04	9.01
3. Aberdeen	95	[3]-29.69	6.69	3.43	8.10
Muscovite	153	-49.94	1.35	-3.12	4.61
Chlorite	153	-91.29	-1.83	-12.11	3.52

[1]Chemical formulas for these phases are as written in WATEQF (Plummer and others, 1978.)
[2]Data from the latest version of WATEQF.
[3]The log equilibrium constant at 25°C is used because no enthalpy is given in WATEQF.

$$(K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2)+2.48H_4SiO_4+0.52Fe^{+3}+0.45Mg^{+2}\rightleftharpoons 3.13H_2O+0.6K^{+1}+1.86H^{+1}+1.56(H_{0.42}Mg_{0.46}Fe_{0.34}Al_{1.47}Si_{3.82}O_{10}(OH)_2). \quad (2)$$

At the phase boundary, the ion-activity product for this reaction will equal the equilibrium constant (K):

$$\frac{[K^{+1}]^{0.6}[H^{+1}]^{1.86}}{[H_4SiO_4]^{2.48}[Fe^{+3}]^{0.52}[Mg^{+2}]^{0.45}}=K. \quad (3)$$

Brackets denote free ion activities, which are concentrations corrected for the nonideality of aqueous solutions. Rewriting in terms of log activities gives the equation:

$$0.61\log[K^{+1}]/[H^{+1}]-0.52\log[Fe^{+3}]/[H^{+1}]^3-0.45\log[Mg^{+2}]/[H^{+1}]^2-2.48\log[H_4SiO_4]=\log K. \quad (4)$$

To plot this line on a two-dimensional graph, the equation must be reduced to two variables. The assumptions that may be considered when plotting phase diagrams include (1) controlling the concentration of a component by equilibrium with a solid phase, (2) conserving a component in solid phases during phase transformations, and (3) assigning a specified concentration for a species in solution, commonly the average for that species in the study area.

In all plots below, it is assumed that the logarithm of the activity quotient of free ferric iron to hydrogen cubed ($\log [Fe^{+3}]/[H^{+1}]^3$) is controlled by the solubility of amorphous ferric hydroxide at 4.885 (Plummer and others, 1978). The average for the log activity ratio of potassium to hydrogen ($\log [K^{+1}]/[H^{+1}]$) in the valley is 2.75, and ratio of magnesium to hydrogen squared ($\log [Mg^{+2}]/[H^{+1}]^2$) is 11.25. The average log activity of silica in ground waters is -3.21. The use of these averages where a concentration must be assumed in the calculation of a phase transformation does not significantly affect the depicted relations between data points and phase boundaries in the following activity diagrams.

For the equilibrium between illite and montmorillonite, $\log [Fe^{3}]/[H^{+1}]^3$ is assumed to be controlled by the solubility of ferric hydroxide, and $\log [H_4SiO_4]$ is assigned a value of -3.21. Replacing these quantities in equation 4 gives the following equation for the phase boundary between illite and montmorillonite:

$$\log [K^{+1}]/[H^{+1}]=0.122+0.743\log [Mg^{+2}]/[H^{+1}]^2. \quad (5)$$

Two types of diagrams are presented here to illustrate phase relations in the system MgO-K_2O-Fe_2O_3-Al_2O_3-SiO_2-H_2O. The diagrams depart, to some extent, from the traditional presentation in that metastable phases are included. Recent work by Paces (1973, 1978) and Busenberg (1978) indicates that during the weathering of feldspars, the initial solids formed are amorphous to poorly crystalline aluminosilicates which may be reversible with respect to the aqueous solution. Subsequent crystallization results in the formation of a metastable aluminosilicate commonly called halloysite. Eventually, the thermodynamically most stable mineral will form. This pathway between primary and secondary minerals generally follows Ostwald's Rule (Darken and Gurry, 1953), which states that when a system is proceeding from a less to a more stable state, the final most stable state is not necessarily reached directly but may be attained through a series of intermediate states. Neither halloysite nor illite are stable with respect to montmorillonite or kaolinite, yet they are present in the sediments. Activity diagrams showing metastable states indicate the intermediate steps, as well as the final secondary minerals that are expected to form.

All minerals included in the following diagrams are from WATEQF and have formulas and log equilibrium constants from that program. Because no information is available on the chemistry of clay minerals from the Sacramento Valley, particularly illite and montmorillonite, no better substitute is available. This use of surrogate minerals will introduce some uncertainty in the exact locations of phase boundaries in the diagrams. Considering the uncertainty in the knowledge of thermodynamic data on montmorillonites and illites, it is doubtful if full knowledge of mineral chemistry would improve the situation. The montmorillonite used in all the diagrams is Aberdeen montmorillonite (Kittrick, 1971) with modifications by Truesdell and Jones (1974).

Figure 12 shows the stability fields of minerals as a function of pH-⅓pAl^{+3} and p[H_4SiO_4], where p stands for -log as in pH=-log [H^{+1}], and pAl^{+3}=-log [Al^{+3}]. This diagram depicts the formation of secondary minerals from an aqueous solution. The solution, in this case, is assumed to have the average ion activity ratios and silica activity observed in the Sacramento Valley. No solid phase will form from solutions with low aluminum to hydrogen ratios and low silica concentrations (bottom right corner of figure 12). At higher aluminum to hydrogen ratios, the stable solid phase changes from gibbsite to kaolinite to montmorillonite with increasing silica. Halloysite and amorphous aluminum hydroxide phase boundaries are dashed to emphasize that they are both metastable phases. A solution in equilibrium with halloysite will be supersaturated with respect to montmorillonite or kaolinite. All samples from the valley plot in the montmorillonite stability field. Only 10 percent of the samples are supersaturated with respect to halloysite.

Regression analysis was used to determine if any significant linear relation exists between aluminum and silica. Each hydrochemical facies was treated separately to preserve as much detail as possible. Only two of the regression equations were significant, those for the Tuscan volcanic rocks and the Sutter Basin facies.

The equation for the Tuscan volcanic rocks facies is

$$pH-\tfrac{1}{3}pAl^{+3}=2.10+0.39p\,[H_4SiO_4] \qquad (6)$$

with r^2 equal to 0.26 and coefficients and their 90 percent confidence limits of

$$2.10 \pm 0.83$$

and

$$0.39 \pm 0.27.$$

Rewriting the equation in terms of log activities gives

$$0.33 \log [Al^{+3}]/[H^{+1}]^3=2.10-0.39 \log [H_4SiO_4]. \qquad (7)$$

The inverse relation between the aluminum to hydrogen ratio and silica is indicative of control by a mineral phase. As silica increases in solution, log $[Al^{+3}]/[H^{+1}]^3$ decreases to compensate.

The slope is close to and not significantly different from 0.33. Assuming that it is 0.33 and rearranging gives

$$\frac{[Al^{+3}][H_4SiO_4]}{[H^{+1}]^3}=10^{6.31}. \qquad (8)$$

The solution of halloysite or kaolinite is given by the equation:

$$\tfrac{1}{2}Al_2Si_2O_5(OH)_4+3H^{+1} \rightleftharpoons \tfrac{1}{2}H_2O+Al^{+3}+H_4SiO_4. \qquad (9)$$

The ion activity product is

$$\frac{[Al^{+3}][H_4SiO_4]}{[H^{+1}]^3}=K. \qquad (10)$$

For halloysite log K equals 6.83 and for kaolinite, 4.76. The close agreement between the ion activity product of halloysite in ground water from the Tuscan volcanic rocks facies with the equilibrium constant is strong evidence that halloysite is controlling the aluminum and silica concentrations in ground water.

The Sutter Basin hydrochemical facies also showed a significant relation between pH-⅓pAl^{+3} and p[H_4SiO_4].

$$pH-\tfrac{1}{3}pAl^{+3}=6.13-0.92p[H_4SiO_4] \qquad (11)$$

with r^2 equal to 0.27 and coefficients and their 90 percent confidence limits of

$$6.13 \pm 2.91$$

and

$$0.92 \pm 0.91.$$

Rewriting the equation in terms of log activities gives

$$0.33 \log [Al^{+3}]/[H^{+1}]^3=6.13+0.92 \log [H_4SiO_4]. \qquad (12)$$

The positive slope is indicative of solution control of water chemistry, with both aluminum and silica increasing as some mineral phase is attacked by hydrogen ion. The slope is close to and not significantly different from one. This gives an aluminum to silica ratio in the dissolving phase of 1 to 3. The most likely minerals are, therefore, potassium and sodium feldspars, which have an aluminum to silica ratio of 1 to 3. This aluminum to silica ratio, along with the etched surfaces of feldspar grains observed under the microscope, may reflect stoichiometric dissolution of feldspars as found by Holdren and Berner (1979) and Berner and Holdren (1979).

Figure 13 shows the phase stability fields for minerals in terms of the log activity ratios of magnesium to

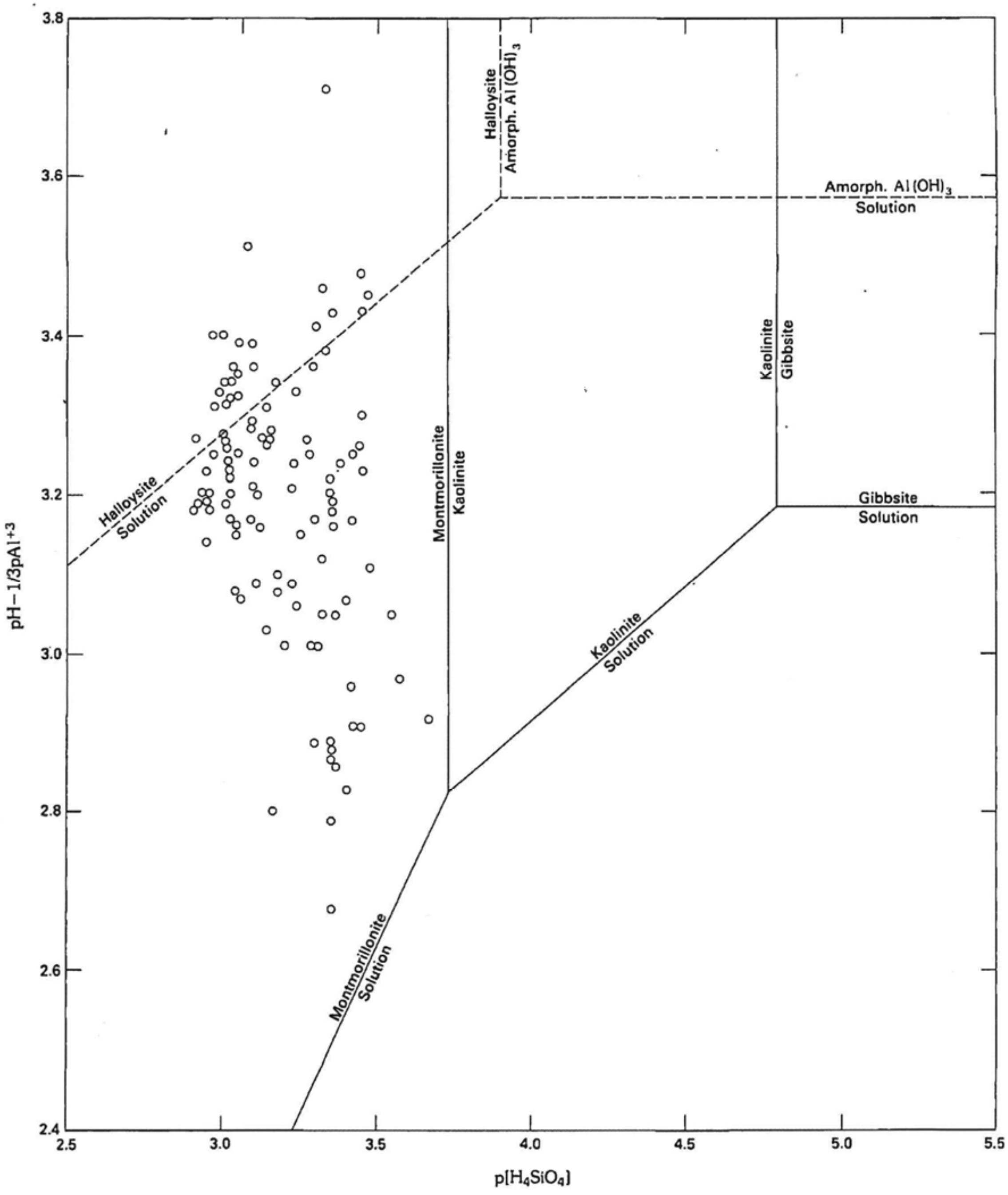

FIGURE 12.—Phase relations among minerals and aqueous solution in terms of pH-⅓pAl^{+3} and p[H_4SiO_4] at 20°C. (NOTE.—The aqueous solution is assumed to have the following ion activity ratios: log [Fe^{+3}]/[H^{+1}]^3 =4.885, log [K^{+1}]/[H^{+1}]=2.75, and log [Mg^{+2}]/[H^{+1}]^2=11.25.)

hydrogen squared and potassium to hydrogen. Aluminum is assumed to be strictly conserved in solid phases during phase transformations. Assumptions about iron and silica activities are as described at the beginning of this section on activity diagrams.

Figure 13 is actually two diagrams superimposed, so that illite, a metastable phase, can be shown. Illite is unstable with respect to montmorillonite or adularia if the three phases are considered simultaneously. The solid lines represent phase relations among the minerals

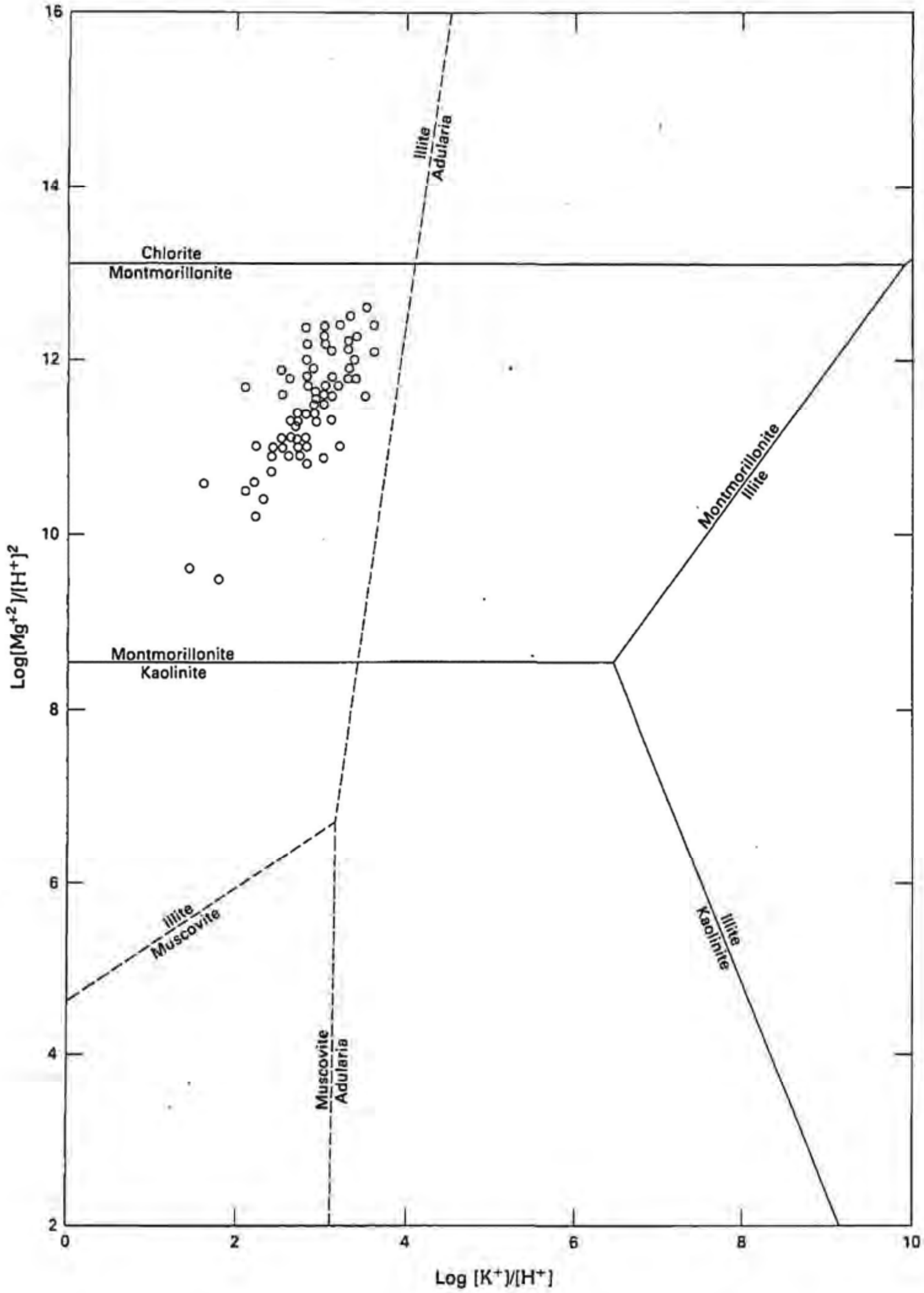

FIGURE 13.—Phase relations among minerals and coexisting aqueous solution in terms of log $[Mg^{+2}]/[H^{+1}]^2$ and log $[K^{+1}]/[H^{+1}]$ at 20°C. (NOTE.—Phase relations among chlorite, montmorillonite, illite, and kaolinite are shown by solid lines, and among illite, adularia, and muscovite by dashed lines. The aqueous solution is assumed to have the following activities of dissolved species: log $[Fe^{+3}]/[H^{+1}]^3$=4.885, log $[H_4SiO_4]$=-3.21.)

chlorite, montmorillonite, illite, and kaolinite. Among these minerals, montmorillonite is the most stable phase in equilibrium with ground water in the valley. The dashed lines represent phase relations among adularia, muscovite, and illite. Of these three minerals, illite is the most stable in contact with Sacramento Valley ground waters.

Illite is highly resistant to weathering (Berner, 1971), and most of the illite found in samples from well 19N/01W-32G is probably detrital. Some of the illite may have formed from the weathering of primary minerals. Illite has been reported to form from orthoclase (Stumm and Morgan, 1970) and from muscovite (Berner, 1971).

Log activities from ground water in the Sacramento Valley plot in the stability field of a montmorillonite having the formula and stability of Aberdeen montmorillonite. Differences in activity ratios of ions in solution will probably produce montmorillonites of somewhat different composition in the Sacramento Valley, but some form of montmorillonite will be the most stable phase. Metastable phases either form as intermediate steps during the diagenesis of primary minerals (halloysite) or persist due to resistance to weathering (illite).

SUMMARY AND CONCLUSIONS

Shallow sediments in the Sacramento Valley were laid down as alluvial deposits in a freshwater environment. These sediments, from which ground-water samples were collected, have always been in contact with freshwater. Sediments along the valley margins are coarse grained, poorly sorted, and oxidized. In the central part of the valley, flood-basin deposits are finer grained and reduced. Most of the streams entering the valley are losing streams, at least over part of their courses, and much of the ground-water recharge is from this source.

The chemistry of ground water in the valley is greatly influenced by the chemistry of this recharge from the valley margins. Approximately one-third of the variation in ground-water chemistry can be attributed to this effect. The reducing conditions and finer grained sediments in the midvalley flood basins also influence ground-water chemistry. These processes have distinct spatial patterns that produce spatial variations in the chemical character of ground water in different areas.

Six areas, or hydrochemical facies, were delineated on the basis of geology, hydrology, and distinctions in chemical composition of ground water. Two of the facies lie along the eastern margin and receive recharge from the Cascade Range and Sierra Nevada. These waters are low in dissolved solids and high in silica. Two facies are located in the midvalley flood basins, and reducing conditions there produce higher concentrations of iron, manganese, and arsenic in the ground water. While the relative concentrations of these species are higher in the flood basins than in the rest of the valley, the absolute concentrations remain fairly low. Upwelling of saline water from underlying marine sediments contributes to high dissolved-solids concentrations in ground water in the southern parts of the flood basins.

Water along the west side of the valley is low in silica, and the water grades from moderate dissolved-solids levels in the north to high dissolved-solids levels in the south. Ground water in the southwest of the valley is also high in boron. The source of the high boron and dissolved-solids concentrations is thermal springs in the Coast Ranges. Two facies were delineated along the western margin to separate the waters having moderate and high dissolved solids. Because of the heterogeneity of ground-water chemistry in the valley, division into areas having more uniform chemical compositions provides additional detail in any investigation of water chemistry.

Dissolved-solids and nitrate concentrations were examined for linear trends with time for each of the hydrochemical facies. Significant increases in both were observed in parts of the valley. On the east side of the valley, the Tuscan volcanic rocks facies showed a significant increase in dissolved solids of 0.95 (mg/L)/yr but no significant change in nitrate concentrations. The Victor Plain facies showed significant increases in both dissolved solids [1.6 (mg/L)/yr] and nitrate-nitrogen [0.036 (mg/L)/yr]. Neither Butte Basin nor Sutter Basin hydrochemical facies, in the midvalley flood basins, showed a significant trend in nitrate with time. There were very few wells with multiple nitrate measurements, however, and the lack of significant changes may be due to the small sample size. Dissolved-solids concentrations in Butte Basin have been increasing at an average rate of 1.37 (mg/L)/yr, but are unchanged in Sutter Basin.

Both the north and south alluvial fans facies, adjacent to the Coast Ranges, show significant upward trends in dissolved solids and nitrate. The south alluvial fans facies has the greatest rate of increase for dissolved solids [4.75 (mg/L)/yr] of all the facies, and the north alluvial fans facies has the greatest rate of increase for nitrate-nitrogen [0.099 (mg/L)/yr]. The midvalley basins have fine-grained poorly permeable soils that protect the ground water from contamination. Infiltration rates are slow, and reducing conditions permit the removal of nitrate by denitrification reactions. Along the valley margins, however, significant increases in dissolved solids and nitrates have occurred since the mid-1950's.

Alkali feldspars and halloysite appear to be the most significant aluminosilicate minerals affecting water chemistry. Where waters are undersaturated, dissolution of feldspars takes place, bringing the water to near saturation with respect to adularia and albite. There is a general parallel increase in aluminum and silica reflecting the solution of aluminosilicates by ground water. In Sutter Basin, the relation between log $[Al^{+3}]/[H^{+1}]^3$ and log $[H_4SiO_4]$ indicates an increase in both aluminum and silica at a ratio 1 to 3. In the Tuscan volcanic rocks facies, the relation between log $[Al^{+3}]/[H^{+1}]^3$ and log $[H_4SiO_4]$ is inverse. Rearranging the regression equation yields the same equation as for equilibrium between halloysite and an aqueous solution. The regression constant is very close to the equilibrium constant for halloysite, which supports the theory of solubility control by halloysite. Illite and halloysite were identified in sediments from the Sacramento Valley. Neither of these clay minerals is stable in the ground-water environment. The most stable clay minerals in equilibrium ground water of the valley is montmorillonite. Halloysite occurs as a mestastable intermediate step in the weathering of primary minerals to stable secondary minerals.

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Late Cenozoic Tectonism of the Sacramento Valley, California

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1359

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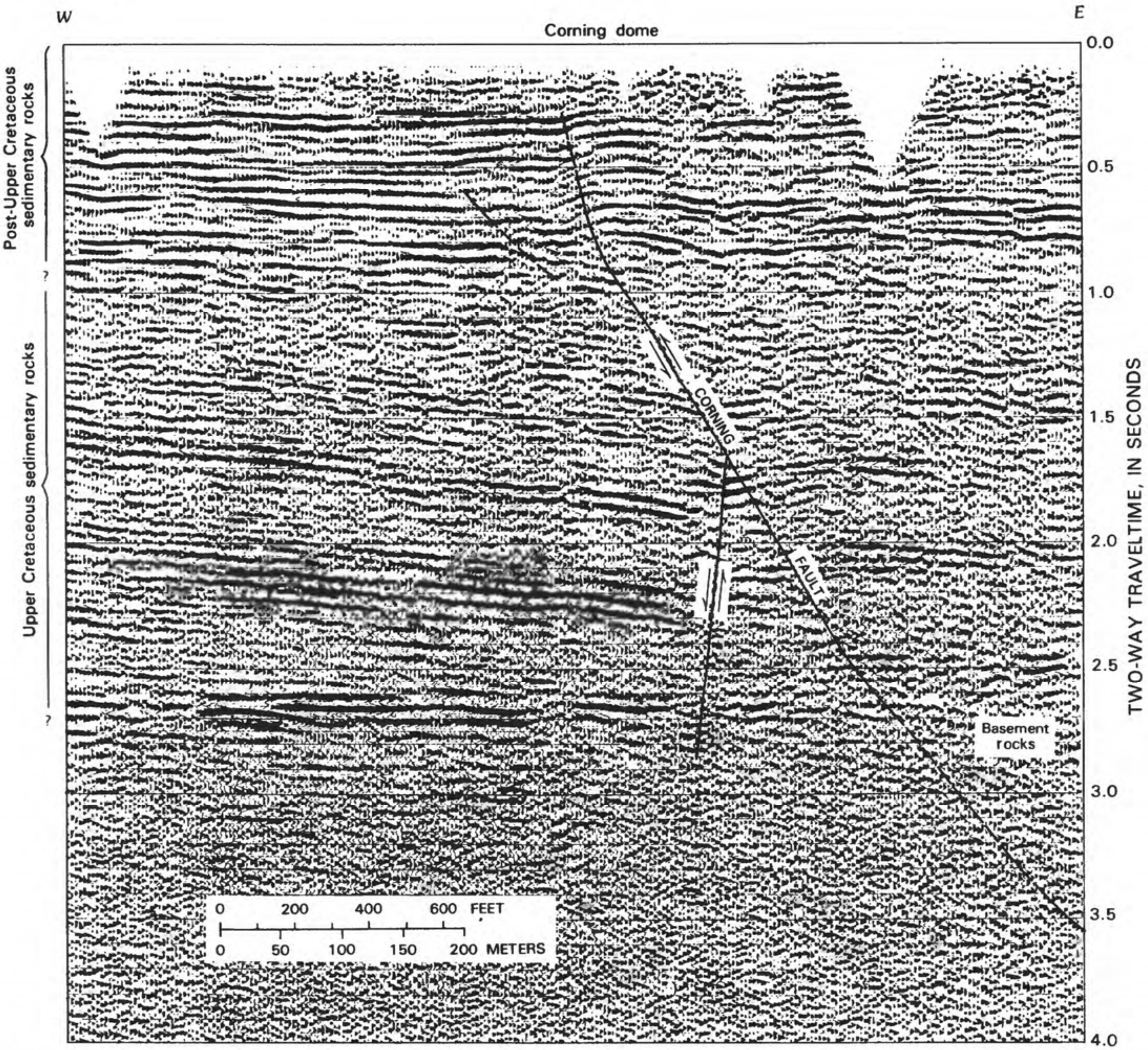

FIGURE 5.—Seismic reflection profile, from Seisdata Services Inc., showing structural and generalized stratigraphic relations across Corning fault between Corning and Red Bluff, Calif.

Late Cenozoic Tectonism of the Sacramento Valley, California

By DAVID S. HARWOOD *and* EDWARD J. HELLEY

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ILLUSTRATIONS

LATE CENOZOIC TECTONISM OF THE SACRAMENTO VALLEY, CALIFORNIA

By David S. Harwood and Edward J. Helley

ABSTRACT

Structure contours drawn on top of the Cretaceous rocks in the Sacramento Valley define a large number of diversely oriented folds and faults that are expressed in topographic, hydrologic, and geologic features at the land surface. Although many of the structures in the valley have a protracted history of movement, some dating back to the late Mesozoic, a remarkable number of these structures show late Cenozoic deformation that can be accurately determined from folding and faulting of widespread, dated Pliocene and Pleistocene volcanic units. These time-stratigraphic units are used to define structural domains of essentially contemporaneous late Cenozoic deformation that was characterized by east-west compressive stress. The oldest structural domain is located in the southeastern part of the valley, where east-side-up reverse movement on the Willows fault ceased prior to deposition of continentally derived sediments of late Miocene and early Pliocene age. In the middle Pliocene to early Pleistocene, east-west compressive deformation progressed northward through the valley so that the youngest late Cenozoic deformation is recorded in east-northeast-trending folds and faults in the Battle Creek domain, at the northernmost part of the valley. The northward progression of east-west compressive deformation appears to be related to the northward eclipse of eastward subduction of the Juan de Fuca plate before the northwestward migration of the Mendocino triple junction along the continental margin west of the valley.

Much of the east-west compressive stress that affected the valley in the late Cenozoic was accommodated by east-side-up reverse movement on the steeply east-dipping, northwest-trending Willows fault and the north-trending Corning fault that splays off from the main stem of the Willows fault north of Sutter Buttes. Significant strain release also occurred on the northwest-trending fault beneath the Chico monocline and on the east-northeast-trending Red Bluff, Battle Creek, and Bear Creek faults in the past 2.0 m.y. Southeast of Sutter Buttes, the Willows fault follows the boundary between dense, magnetic, presumably ophiolitic basement to the west and Sierran basement to the east. The Chico monocline follows the same basement boundary north of Sutter Buttes, but that structure is stepped eastward from the trace of the Willows fault. It seems reasonably certain that the southeastern extension of the Willows fault and the Chico monocline fault are middle and late Cenozoic structures, respectively, that owe their existence and orientation, in part, to earlier, Mesozoic tectonic juxtapositioning of significantly different basement terranes.

INTRODUCTION

The Oroville earthquake ($M = 5.6$, August 1, 1975) added a new dimension to geologic studies of the Sacramento Valley. That event, more than any of the infrequent earthquakes that previously occurred in the area, awakened the geologic and engineering communities to the potential of active faulting in the valley and in the adjacent Sierran foothills. Because the Oroville earthquake occurred near the Lake Oroville dam (fig. 1) at a time when other large dams were being constructed along the Sierran foothills, several geologic studies, including this one, were conducted to specifically evaluate the late Cenozoic structural history of the region (Woodward-Clyde Consultants, 1977; Harwood and others, 1981; Helley and others, 1981; Helley and Harwood, 1985).

For about a half century prior to the Oroville earthquake, most geologic investigations of the Sacramento Valley (fig. 1) focused on locating natural gas in the deeper parts of the valley fill and water resources in the near-surface deposits. These investigations produced a wealth of stratigraphic and structural data that was gathered primarily from numerous gas fields scattered throughout the valley (map A, pl. 1). Several geologic syntheses resulted from these studies, but they were designed primarily to facilitate further exploration for these valuable resources and did not emphasize late Cenozoic tectonism (Bryan, 1923; Repenning, 1960; Olmsted and Davis, 1961; Safonov, 1968; Hackel, 1966; Redwine, 1972; California Department of Water Resources, 1978).

Recent developments in the concept of plate tectonics have given new emphasis and scope to regional geologic analyses by enabling integration of studies in the valley with those in the Coast Ranges to the west and the Sierra Nevada to the east (fig. 2). Within this concept, the Sacramento Valley was interpreted to be a late Mesozoic forearc basin (Dickinson, 1970; Ingersoll, 1976, 1978a, 1978b; Dickinson and Seely, 1979) that formed contemporaneously with and between the accretionary trench deposits of the Franciscan Complex to the west (Ernst, 1965, 1970; Blake and Jones, 1974; Blake and others, 1974) and an eastern magmatic arc complex, the roots of which are exposed in the Sierra Nevada (Hamilton, 1969). Although debate about the extent, geographic origin, and nature of the material accreted to the Mesozoic continental margin continues (Coney and others, 1980), the basic three-component model of an arc-trench system remains fundamental (Dickinson and Seely, 1979). Although the Sacramento Valley may be the most completely studied ancient forearc basin in the world (Ingersoll and others, 1977), the emphasis and scope of published paleogeo-

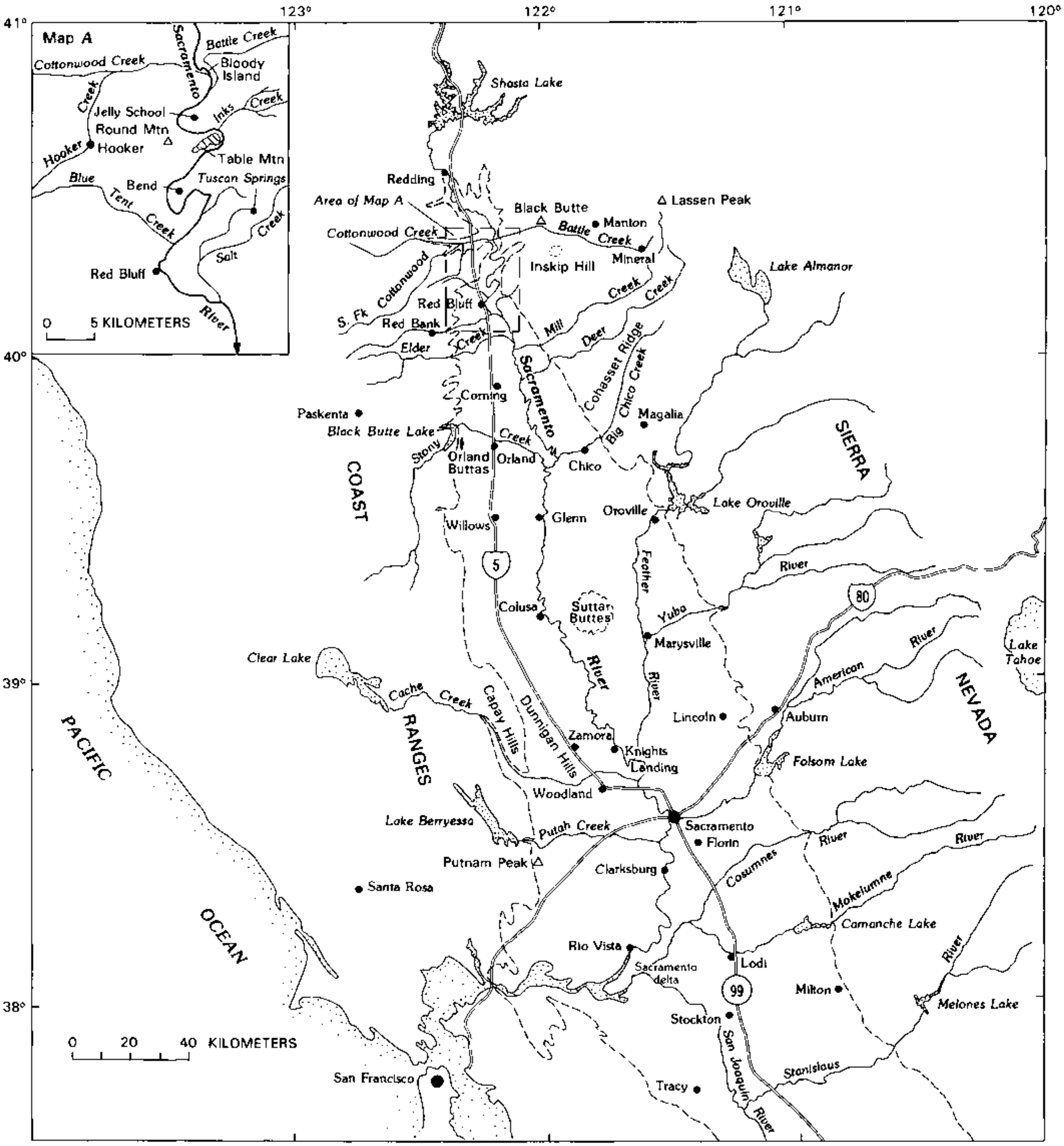


FIGURE 1.—Index map of northern California showing 500-foot topographic contour (dashed), which coincides approximately with boundary of Sacramento Valley.

graphic and paleotectonic studies generally precluded detailed analysis of late Cenozoic tectonism.

Structures discussed in this report are generally too young to provide new data for the late Mesozoic arc-trench model. In fact, a major objective of this report is to document that most of the folds and faults in the valley either formed in the late Cenozoic or are older structures that have undergone renewed deformation in the past few million years. In this respect, structures in the valley are more closely related to tectonic models of Cenozoic subduction, including subsequent lateral convergence along the San Andreas fault system and extension in the Basin and Range province to the east, than they are to the late Mesozoic tectonic models (Hamilton and Myers, 1966; Atwater, 1970; Christiansen and Lipman, 1972; Atwater and Molnar, 1973; Dickinson, 1979).

ACKNOWLEDGMENTS

The structure contour map presented in this report (pl. 1) integrates subsurface data from many summary reports of oil and gas operations published by the California Division of Oil and Gas. Credit is given to specific authors of gas field reports in the "Sources of Data" shown on plate 1, and we would like to express our appreciation to those authors, whose work contributed much of the basic data for our compilation. In addition to published reports, we analyzed well logs from a number of areas in the valley, and we acknowledge the courteous service provided by the staff of the Woodland office of the California Division of Oil and Gas.

Interpretation of the subsurface data was influenced to a great degree by exceptionally high-quality seismic-reflection profiles purchased from Seisdata Services Inc. We thank Seisdata Services Inc. for allowing us to reproduce a small segment of one of those profiles in this report.

We thank David Wagner of the California Division of Mines and Geology for sending us a preprint of his detailed map and discussion of the Capay Valley-Capay Hills area. Special thanks are given to the California Academy of Sciences for making available their collection of thin sections of basement rocks that were penetrated in wells in the Sacramento Valley.

We also acknowledge stimulating discussions with our colleagues J.A. Bartow, M.C. Blake, Jr., K.F. Fox, Jr., D.L. Jones, R.J. McLaughlin, T.H. Nilsen, A.M. Sarna-Wojcicki, and C.M. Wentworth. These discussions sharpened the focus of many points in this report, but responsibility for the analysis of subsurface structures and regional tectonism rests with Harwood, and the mapping of surficial deposits, which document the youthfulness of many structures, rests with Helley.

REGIONAL SETTING

The Sacramento Valley comprises the northern third of the Great Valley of California (fig. 2)—a broad, fertile lowland situated between mountainous terrains of the Coast Ranges to the west and the Sierra Nevada to the east. Marine sedimentary rocks, ranging in age from Late Jurassic to early Miocene, underlie the deeper parts of the Sacramento Valley. They are unconformably capped by a relatively thin cover of alluvial deposits and locally prominent volcanic rocks of early Miocene to Holocene age.

Marine sedimentary rocks exposed on the west flank of the Sacramento Valley record a nearly unbroken depositional sequence from Upper Jurassic through Upper Cretaceous (Lachenbruch, 1962; Ingersoll and others, 1977). On the east side of the valley, Upper Cretaceous sandstone and shale, described by Taft and others (1940) and Haggart and Ward (1984), rest unconformably on metamorphic and plutonic rocks of the Sierra Nevada basement and indicate a progressive eastward onlap of marine sedimentation during the late Mesozoic (Ingersoll and others, 1977). In a broad area south of Sutter Buttes, younger Upper Cretaceous sandstone and shale record a westward-prograding deltaic sequence and marine regression (Drummond and others, 1976; Garcia, 1981) during the Late Cretaceous, as the depositional basin was broadly uplifted and tilted to the south and west. Intermittent periods of uplift and subsidence, apparently caused by Paleogene subduction and possibly by lateral faulting to the west (Nilsen and Clarke, 1975; Nilsen and McKee, 1979), affected the depositional basin through the early Tertiary.

Four distinct submarine canyons developed during the uplift cycles, and they were subsequently filled with transgressive marine sequences during times of subsidence (fig. 2). Almgren (1978) has documented three ancient oscillatory tectonic-depositional cycles in the southern part of the Sacramento Valley. He concludes that the Martinez canyon was cut in the late early to middle Paleocene, the Meganos canyon was cut in early Oligocene and filled in late Oligocene and early Miocene, and the Markley canyon was cut in early Oligocene and filled in early Miocene time. Although the timing of the fourth submarine canyon is not as closely constrained by the sedimentary record as the other three, Redwine (1972) concluded that the Princeton canyon, located in the north-central part of the valley (fig. 2), was cut and filled between the late Paleocene and early Eocene, probably coincident with the formation of the Martinez canyon to the south (Almgren, 1978). Eocene marine deposits in the Princeton canyon apparently grade northward and eastward into alluvial deposits derived from the northern Sierra Nevada.

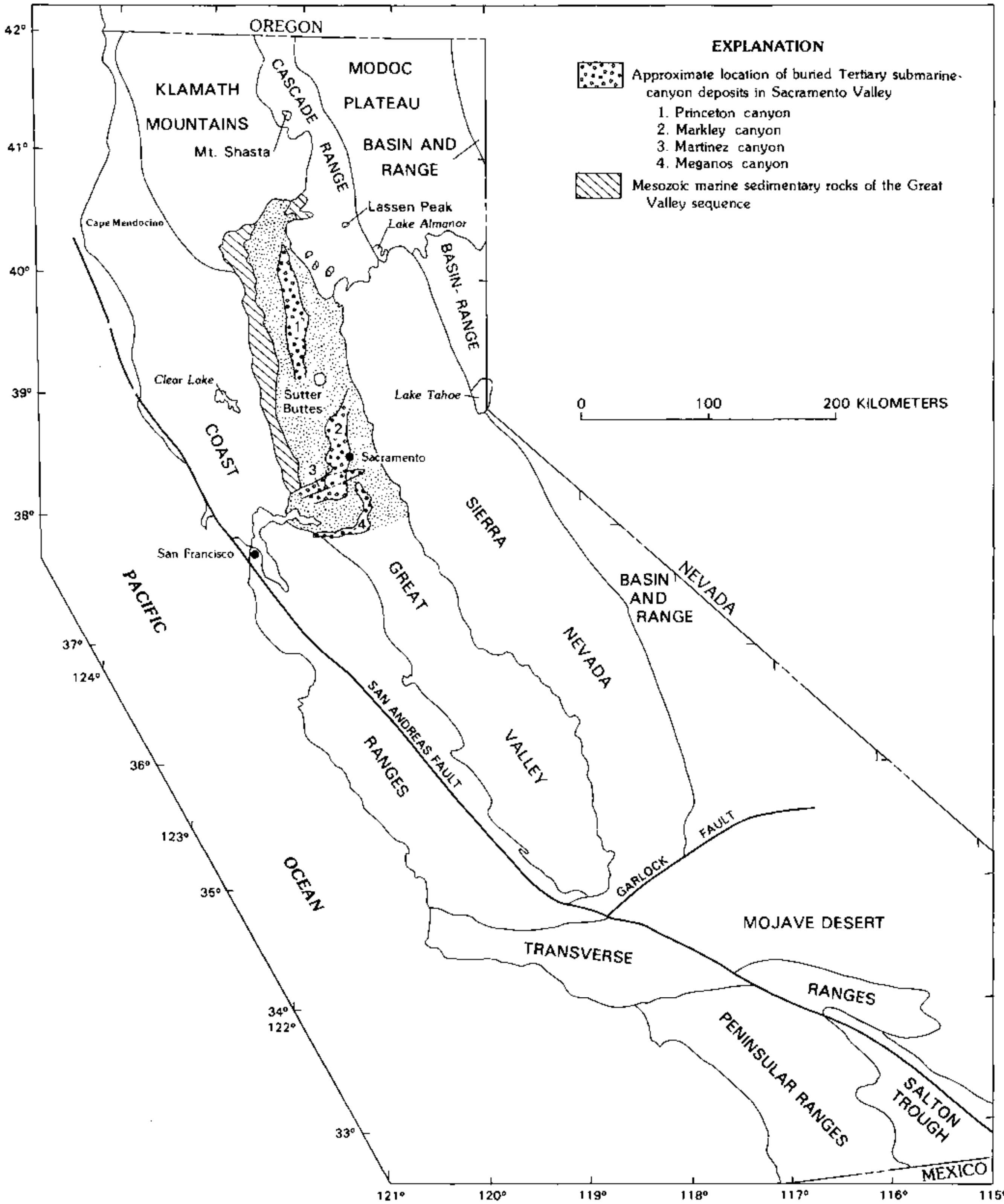


FIGURE 2.—Outline of geomorphic provinces in California and general location of buried Tertiary submarine canyon deposits in Sacramento Valley (stippled).

By the early Miocene, the northern part of the Sacramento Valley clearly was an emergent area, subjected to fluvial erosion and deposition. During this time, between 23.8 and 22.3 m.y. ago according to Dalrymple (1964), the Lovejoy Basalt was erupted from a vent or vents in the northern Sierra Nevada (Durrell, 1959) and flowed westward in a confined channel until it reached the Sacramento Valley near Oroville. Upon reaching the valley, the Lovejoy Basalt spread laterally, filling distributary alluvial channels (van den Berge, 1968) and flowed both westward, across the present axis of the valley now occupied by the Sacramento River at least to Orland Buttes, and southward at least to the vicinity of Putnam Peak (Weaver, 1949) (fig. 1), 260 km from the presumed source. Because of its distinctive characteristics, widespread distribution in both the surface and subsurface parts of the Sacramento Valley, and radiometrically determined age, the Lovejoy Basalt is an important marker unit (pl. 1) that places an age constraint on Cenozoic deformation in the valley.

After eruption of the Lovejoy Basalt, alluvial sediments of late middle Miocene to early Pliocene age accumulated in the central and southern part of the valley, capping marine sedimentary rocks deposited in the Princeton and Markley canyons (Redwine, 1972; Almgren, 1978). These alluvial deposits, however, are not present in surface exposures in the northern part of the valley, where Pliocene alluvium of the Tehama Formation in the northwest and coeval volcanic rocks of the Tuscan Formation in the northeast rest directly on the Lovejoy Basalt or on older rocks where the Lovejoy is missing.

A widespread felsic pumiceous tuff, the Nomlaki Tuff Member of the Tuscan and Tehama Formations, occurs at or near the base of the Pliocene rocks and serves as a second important time-stratigraphic marker in the valley, dated at 3.4 m.y. (Evernden and others, 1964). The Nomlaki, which was erupted from the vicinity of Lassen Peak, generally marks the beginning of volcanic activity that has occurred intermittently into historic time at the southern end of the Cascade Range (fig. 2). Pliocene and Pleistocene volcanic rocks, erupted from the Lassen area, flowed westward and interfingered with alluvial deposits of the ancestral Sacramento River system in the northern part of the valley (Anderson, 1933; Lydon, 1968; Harwood and others, 1981; Helley and others, 1981). Several of the volcanic units have been dated (Harwood and others, 1981), and they are important time indicators for the late Cenozoic depositional and tectonic evolution of the Sacramento Valley. Two informally designated volcanic units, the Rockland ash bed (referred to as the ash of Mount Maidu by Harwood and others, 1981) and the basalt of Deer Creek, dated at 0.45 and 1.09 m.y., respectively (Meyer and others, 1980; Harwood and others, 1981), are particularly significant because they bracket the age of the Red Bluff Formation. The Red Bluff forms a thin, widespread gravel pediment that unconformably caps the Pliocene rocks in the northern part of the valley. The fact that the Red Bluff Formation is faulted and folded clearly establishes the presence of late Cenozoic deformation, within the past million years, on most of the major features shown on the structure contour map (pl. 1).

A volcanic center, composed of andesitic fragmental deposits intruded by late-stage rhyolite domes, formed at Sutter Buttes in the central part of the valley between 2.4 and 1.4 m.y. ago (Williams, 1929; Williams and Curtis, 1977). This late Cenozoic volcanic center is located over a northwest-trending tectonic boundary that juxtaposes a basement of dense, magnetic, presumed oceanic crust (Cady, 1975; Griscom, 1973) on the west against metamorphic and plutonic rocks of the Sierran basement on the east. The boundary between the basement terranes is a Mesozoic tectonic feature that apparently has been reactivated by Cenozoic deformation (Harwood, 1984). Southeast of Sutter Buttes, the Willows fault approximately follows the contact between oceanic and Sierran basement terranes, and northeast of Sutter Buttes that basement boundary lies beneath the Chico monocline.

In the southeastern part of the valley, structure contours are drawn on the basement surface (pl. 1). In the rest of the valley, the datum is the top of the Cretaceous rocks. Contouring procedures are described on plate 1.

INTERPRETATION OF BASEMENT CONTOURS

The most pronounced deflection in basement contours is located beneath Sutter Buttes (pl. 1). This anomaly in basement topography was shown first by Smith (1964) and mentioned briefly by Williams and Curtis (1977, p. 6), who noted more than 395 m of local relief on the basement surface but offered no interpretation of the anomaly. Although some of the upwelling of the basement surface may be related to volcanic intrusion at Sutter Buttes, Harwood (1984) suggests that much of the basement uplift was related to east-side-up movement on the Willows fault, which passes just west and south of the Sutter Buttes.

Data from deep wells a few kilometers north of Sutter Buttes (pl. 1) indicate that the basement surface has a major deflection related to a northeast-trending fold or fault, or both. All of these possible structural configurations were investigated, and we conclude that the structure in the area is a northeast-trending fold, faulted along its southeast limb. The fault is interpreted to be a steeply dipping to vertical normal fault with southeast-side-down displacement. Both the fold and fault, however, appear to die out to the northeast.

In a zone southeast of Sutter Buttes that extends to the Stockton fault (pl. 1), variations in the slope of the basement surface are shown by northwest-trending zones of broadly spaced and relatively close-spaced contours. The basement surface may dip eastward locally in those areas marked by broadly spaced contours (see Jacobsen, 1981), but well data are too sparse to locate closed contours in this area, even if they would show at the chosen contour interval of 150 m.

From Sacramento south to the Stockton fault, the slope of the basement steepens significantly west of the −1,500-m contour. This change in basement slope lies near the eastern edge of the positive gravity and magnetic anomalies in the Great Valley that Cady (1975) interpreted to represent ophiolitic oceanic crust tectonically juxtaposed against Sierran basement rocks to the east. Reports of two wells south of Sacramento, however, show "granite" and "gneiss" at −1,954 m and −2,861 m, respectively, suggesting that the interpreted suture between oceanic and Sierran basements is not marked by the topographic break in the basement surface at the −1,500-m contour. It must be emphasized, however, that these identifications of basement rocks were made some time ago by the operators who drilled the wells, and it is possible that the "granite" may be a leucocratic rock associated with ophiolitic basement, such as plagiogranite, and the "gneiss" may be any dark-colored rock, even part of the ophiolitic basement. It seems reasonably certain, in any case, that the topographic break at the −1,500-m contour is controlled in some measure by a fault, possibly the extension of the Willows fault southeast of Sutter Buttes. It is interesting, and not altogether fruitless, to speculate that the Willows fault southeast of Sutter Buttes coincides with and represents the up-section propogation of the major fault between oceanic crust and the arc-massif basement of the Sierra Nevada. If such is the case, the Willows fault southeast of the Sutter Buttes may represent a structure inherited from the upper-slope discontinuity, a region of structural weakness over the boundary between forearc-basin and arc-massif basements, identified by Karig and Sharman (1975) in modern forearc basins.

From Sutter Buttes north to Chico, a number of wells penetrate basement rocks reported as diorite, gabbro, noritic gabbro, and serpentine. Not surprisingly, this part of the Sacramento Valley is characterized by large, positive gravity and magnetic anomalies that mark the northern part of the inferred Great Valley ophiolitic basement (Cady, 1975). Some thin sections of gabbro and diorite from wells in this area, contained in a collection of thin sections of basement rocks held by the California Academy of Sciences, reveal remarkably fresh coarse- and medium-grained clinopyroxene-plagioclase rocks that show pronounced cumulate textures. These textures, previously unrecognized, provide supporting evidence for the interpretation that the source rocks of the Great Valley anomaly are oceanic crust.

South and east of Sutter Buttes, several wells penetrate rocks reported as granite, granodiorite, metavolcanic rocks, and "gneiss" typical of rocks exposed in the Sierran foothills. The outline of granitic plutonic rocks, shown on plate 1, was determined from reported basement rocks, augmented by our interpretation of residual isostatic gravity data (Roberts and others, 1981). The boundary between the Sierran basement and mafic and ultramafic rocks of probable ophiolitic basement trends about N. 45° E. from Sutter Buttes to Oroville. It is clearly marked by significant changes in the gravity and magnetic patterns of the respective areas. The basement contours do not reflect this inferred lithologic change, and the northeast-trending fault north of Sutter Buttes is contained within the mafic-ultramafic basement terrane.

Sierran crystalline rocks are exposed in several deep canyons that cut through the Pliocene volcanic rocks of the Tuscan Formation east of Chico (Harwood and others, 1981). The mafic-ultramafic basement appears to abut against Sierran basement rocks along a major basement fault beneath the Chico monocline. This tectonic juxtaposition of basement terranes was proposed first by Griscom (1973), and the basement fault he proposed from geophysical data is confirmed by stratigraphic data. The basement fault beneath the Chico monocline shows east-side-up displacement with a minimum stratigraphic throw of 367 m on the basement surface. This fault represents late Cenozoic deformation superposed on a segment of the late Mesozoic boundary between the forearc-basin and arc-massif basements, and it is thus part of the upper-slope discontinuity (Karig and Sharman, 1975).

STRUCTURAL FEATURES IN THE VALLEY FILL

Structure contours drawn on top of the Cretaceous rocks outline a large number of diversely oriented folds and faults distributed throughout the valley. Some of these structures, such as the Corning domes, the Chico monocline, and the Dunnigan Hills anticline, have topographic expression and were recognized in the early ground-water studies of the valley by Kirk Bryan (1923). Most of the other structures do not have obvious surface expression, and they were discovered during exploration and development of the numerous small gas fields in the valley (pl. 1, map A). Although detailed reports have been published for many of the gas fields, few reports have synthesized the data from these studies into detailed structural analyses of the valley as a whole. Noteworthy exceptions to this generalization exist, however, and include the early stratigraphic and structural synthesis by Safonov (1968), the detailed study of the Princeton submarine channel system by Redwine (1972), and the continuing efforts of the California Division of Mines and

Geology to compile available data from the valley into small-scale maps of the entire state (Jennings, 1977).

The extent of many of the faults, particularly the complex pattern of the Willows fault and the relations between that fault system and many folds in the northern valley, has not been reported previously. Analyses of well logs, which are the basis for most reports of individual gas fields, do not provide sufficient data to interpret unequivocally the structure of each field. If recognizable stratigraphic units in the well logs are at different elevations in adjacent wells, it is generally impossible to determine if the units are offset by folding or faulting, or both, without additional data from surface exposures or seismic-reflection profiles. Our interpretation of the structural relations in the valley is based on data from well logs, augmented by detailed mapping of the surficial deposits by Helley, and exceedingly valuable seismic-reflection data obtained from Seisdata Services Inc.

WILLOWS FAULT SYSTEM

The main stem of the Willows fault was discovered in the subsurface rocks of the northern valley when it was penetrated by the Marathon Oil Company (formerly Ohio Oil Company) "Capital Company No. 1" well during development of the Willows-Beehive Bend gas field in the late 1950's (California Division of Oil and Gas, 1960; Alkire, 1962; 1968). From the discovery well, Redwine (1972) traced the Willows fault in the subsurface southeast to Sutter Buttes and suggested that it extended northwest of the discovery well, possibly connecting with the surface fault mapped west of the Orland Buttes (Anderson and Russell, 1939; Jennings and Strand, 1960). On the basis of the distribution of Quaternary units immediately south of Orland Buttes and of two seismic profiles north of the buttes, we have extended the Willows fault into northwestern Tehama County. At Orland Buttes, Upper Cretaceous rocks, the Lovejoy Basalt, and the Tehama Formation, on the up-thrown side of the Willows fault, are juxtaposed against the Tehama Formation on the down-thrown fault block to the west.

Redwine (1972) documented displacement on a 40-km segment of the main stem of the fault from east of Willows to Sutter Buttes and concluded that it dipped 74° or steeper to the east and showed reverse, east-side-up movement that decreased upward toward the surface. He found that the Princeton submarine channel was localized by movement on the fault and that vertical separation in the discovery well varied from about 488 m on top of the Cretaceous rocks to about 477 m on the top of the Eocene Capay Formation.

The pattern of deformation on the Willows fault and its effect on the thickness and facies patterns in the Capay Formation are clearly shown in figure 3. In this approximately east-trending cross section through the Marathon "Capital Company No. 1" well (No. 3, fig. 3), the thalweg of the Princeton channel, which is occupied by marine shale of the Capay, coincides with a syncline in the underlying Upper Cretaceous rocks. The west limb of the complementary anticline in the Upper Cretaceous rocks is broken by east-side-up movement on the Willows fault. The electric logs show that west of the fault the Capay is composed of shale, and east of the fault it is dominantly sandstone that interfingers with shale eastward toward the thalweg of the channel. Folding and faulting clearly postdated the deposition of Upper Cretaceous strata and preceded the deposition of the Capay and occurred between about 60 and 53 m.y. ago. During that time there was some erosion of the Upper Cretaceous rocks, particularly along the channel thalweg. The westward increase in sandstone and a complementary decrease in thickness of the Capay toward the fault suggest that the anticlinal welt of Upper Cretaceous rocks was a shoal area during Capay deposition. Because the shale-rich Capay west of the fault is about the same thickness as the sandstone-rich Capay east of the fault, there appears to have been little, if any, deformation on the Willows fault in this area during deposition of the Capay. The section shows about 475 m of post-Capay offset and possibly small offset on the base of the Tehama, but the amount of post-Pliocene offset is difficult to determine because there is no record for the upper part of well 2 (fig. 3).

CORNING FAULT

Data from a number of sources indicate that the Willows fault is far more extensive and complex than previously thought. The first clue that the Willows fault branched into a multistrand fault system was provided by an analysis of seismicity of the northern valley and Sierran foothills after the Oroville earthquake. Marks and Lindh (1978) located a number of small-magnitude earthquakes along a zone that originated near the Marathon "Capital Company No. 1" well in the Willows-Beehive Bend gas field and extended north about 30 km, rather than following the northwest trend of the Willows fault. These epicenters are shown relative to the trace of the Willows fault in figure 4. The trend of seismic events suggests that a north-trending fault splayed off from the main stem of the Willows fault and passed west of the Corning domes (pl. 1). In the Corning gas fields, analysis of well records by the Sacramento Petroleum Association (1962) showed an anticlinal fold in the area of the Corning domes, with about 121 m of maximum closure on the base of the Tehama Formation in the north dome and a steeply dipping southeast-trending fault located at the north end of south Corning dome, but it did not identify a fault west of them.

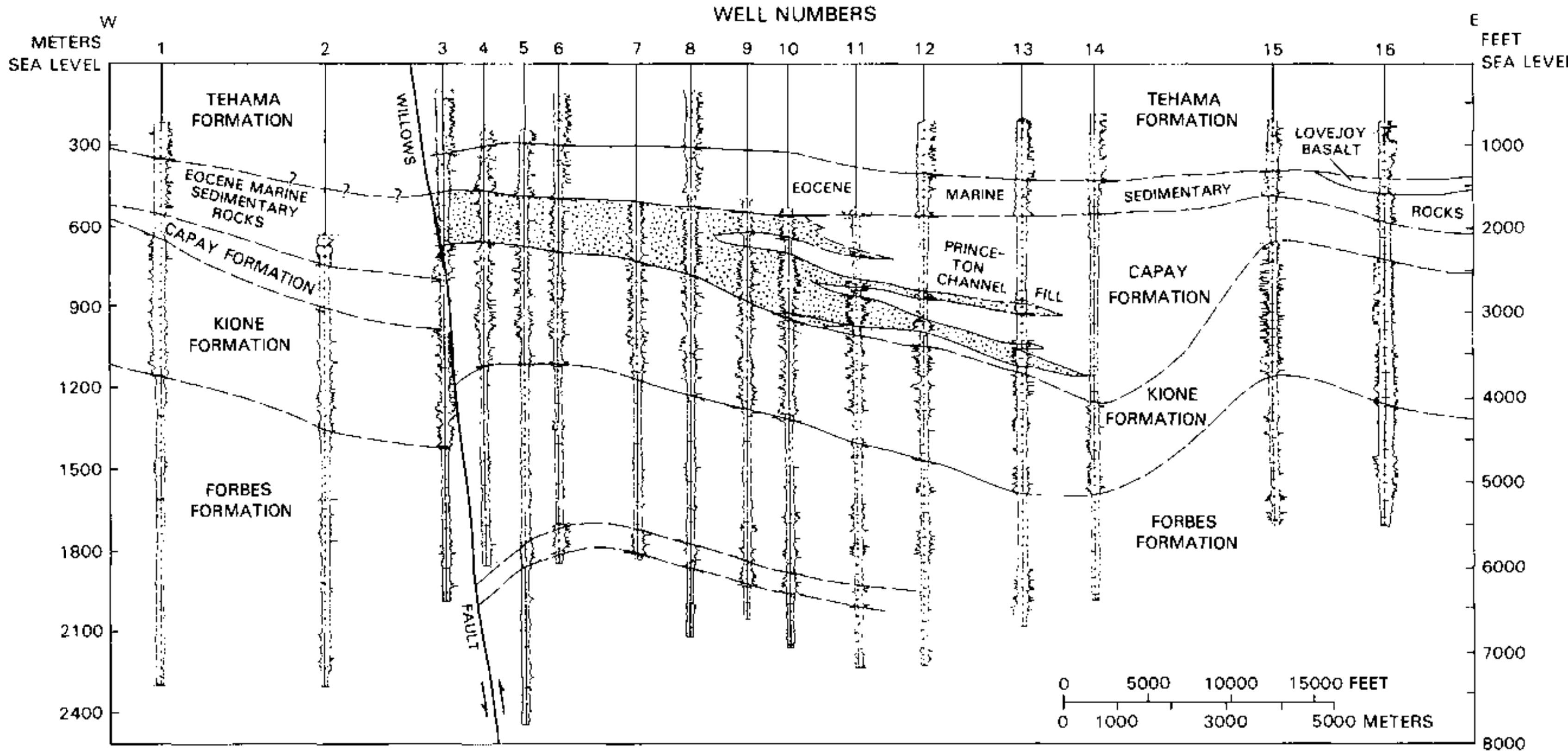


FIGURE 3.—Cross section showing electric logs and stratigraphic and structural relations across Willows-Beehive Bend gas field, Calif. Sandstone in Capay Formation indicated by stipple. Willows fault penetrated in well No. 3. Names of wells shown in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

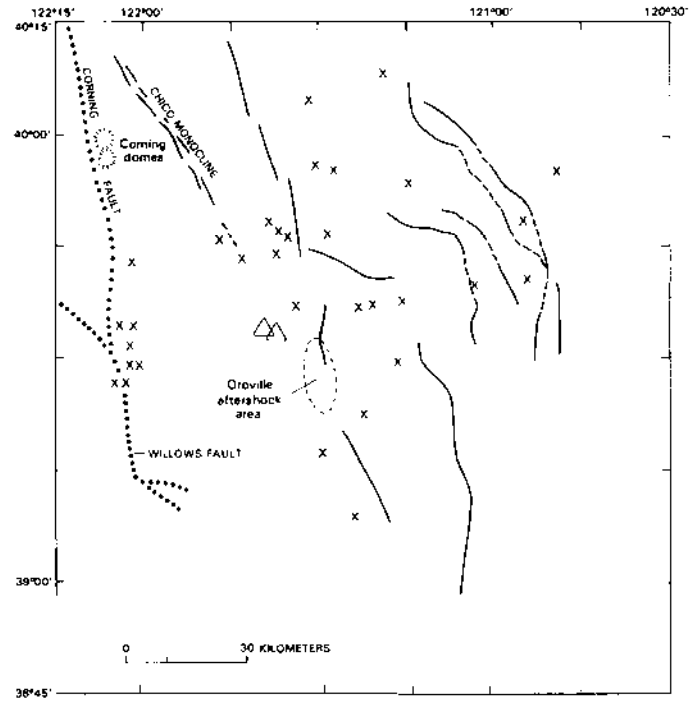


FIGURE 4.—Epicenters (X) of seismic events in area of Oroville, Calif., from June 1975 to August 1976 (modified from Marks and Lindh, 1978). Note north trend of epicenters extending from Willows fault approximately along trace of Corning fault. Unlabeled heavy lines indicate other faults. Triangles show epicenters of two unusually deep (40 km) earthquakes.

Seismic-reflection profiles in the area by Seisdata Services Inc. have identified a major north-trending, steeply east-dipping reverse fault that passes west of the Corning domes and the Greenwood anticline. We call this structure the Corning fault (pl. 1), and part of one of the profiles across it is shown in figure 5. The profile clearly shows that the shallow reflecting horizons in the eastern block are arched beneath the Corning dome by east-side-up drag on the Corning fault. It is also apparent in the profile that the vertical displacement increases with depth, indicating progressive deformation through time, similar to the deformation pattern on the main stem of the Willows fault in the Willows-Beehive Bend gas field (fig. 3). Curiously, however, the amount of vertical displacement of the Upper Cretaceous and younger strata shown on the profile is relatively small compared to the offset of the basement surface suggested by the few deep wells in the area shown on figure 6.

The deepest well east of the Corning fault is the Shell Oil Company "Victor Ranch No. 4" (sec. 7, T. 23 N., R. 2 W.), which bottomed in the Venado Sandstone of Late Cretaceous (Turonian) age at an elevation of −3,713 m (fig. 6). Lithologic information from this well helps interpret the seismic-reflection profile, and its total depth provides a minimum value for the basement elevation 8 km east of the Corning fault. Although local variations in the slope of the basement surface exist, the basement generally dips about 5° SW. between the Chico monocline and the Corning fault. The intersection of the basement surface and the Corning fault ranges in elevation from about −3,900 m in the north to about −4,600 m in the south. This south-southeast plunging line of intersection appears to lie significantly above the basement surface west of the Corning fault.

West of the Corning fault, only one well, the Shell Oil Company "Vilche No. 2" (sec. 5, T. 27 N., R. 4 W.), reached basement, which was serpentinite penetrated at an elevation of −5,978 m (fig. 6). Data from this well are not sufficient to determine the dip of the basement surface west of the Corning fault, but the dip immediately west of the fault may be the same as that just east of the fault, assuming that the basement surface was not chaotically tilted prior to deposition of the Great Valley sequence. If such is the case, the −6,000-m contour can be extrapolated south of the Shell Oil Company "Vilche No. 2" well parallel to the contours east of the Corning fault, as shown on figure 6. This extrapolation gives a vertical separation of about 1,500 m on the basement surface if one assumes no offset on the Red Bluff fault (fig. 6). Because the Red Bluff fault (discussed in a following section of this report) shows down-to-the-south displacement of the valley fill, similar basement offset on the Red Bluff fault would increase the basement separation on the Corning fault. Therefore, 1,500 m of vertical offset on the basement surface across the Corning fault is considered to be a minimum value.

The reason why the basement offset does not appear on the seismic reflection profile is not known. Perhaps the energy input was not sufficient to generate reflections from the deeper basement. Alternatively, the Venado Sandstone, which thickens westward, may have masked reflections from older rocks of the Great Valley sequence and the basement surface west of the Corning fault. Whatever the reason, geologic data strongly suggest that the basement was offset at least 1,500 m on the Corning fault prior to Turonian time and that pre-Turonian rocks of the Great Valley sequence, deposited on the downdropped block of the fault were unconformably overlapped by the Venado Sandstone. Post-Turonian displacement on the Corning fault is a few hundred meters.

The youngest deposits deformed by the Corning fault are gravels of the Pleistocene Red Bluff Formation, the age of which is between 0.45 and 1.09 m.y. (Harwood and others, 1981).

NORTHWEST EXTENSION OF WILLOWS FAULT

The location of the Willows fault system north and northwest of Orland Buttes is not clearly indicated by direct evidence in either the surface or subsurface rocks.

Wells are sparse in this area of the valley, particularly west of the probable trace of the main stem of the Willows fault. For that reason, the structure contours are very generalized and of little value in locating even major structures.

Our projection of the Willows fault into the Cold Fork, Elder Creek, and Paskenta faults (pl. 1) mapped by Jones and others (1969) is based primarily on the outcrop pattern of the Tehama Formation. North of Elder Creek, the Tehama Formation dips gently east, and the Nomlaki Tuff Member is at the base of the Tehama or is, at most, a few tens of meters above its base. South of Elder Creek, however, the Tehama dips more steeply eastward into the valley, and the Nomlaki is a few hundred meters above the base of the Tehama. This outcrop pattern of the Tehama Formation suggests that the underlying Great Valley sequence was topographically higher and projected farther east into the valley north of the Willows fault prior to deposition of the Pliocene strata. The position of the Nomlaki Tuff Member, relative to the base of the Tehama on opposite sides of the Willows fault, indicates that the Tehama filled a topographic low southwest of the fault

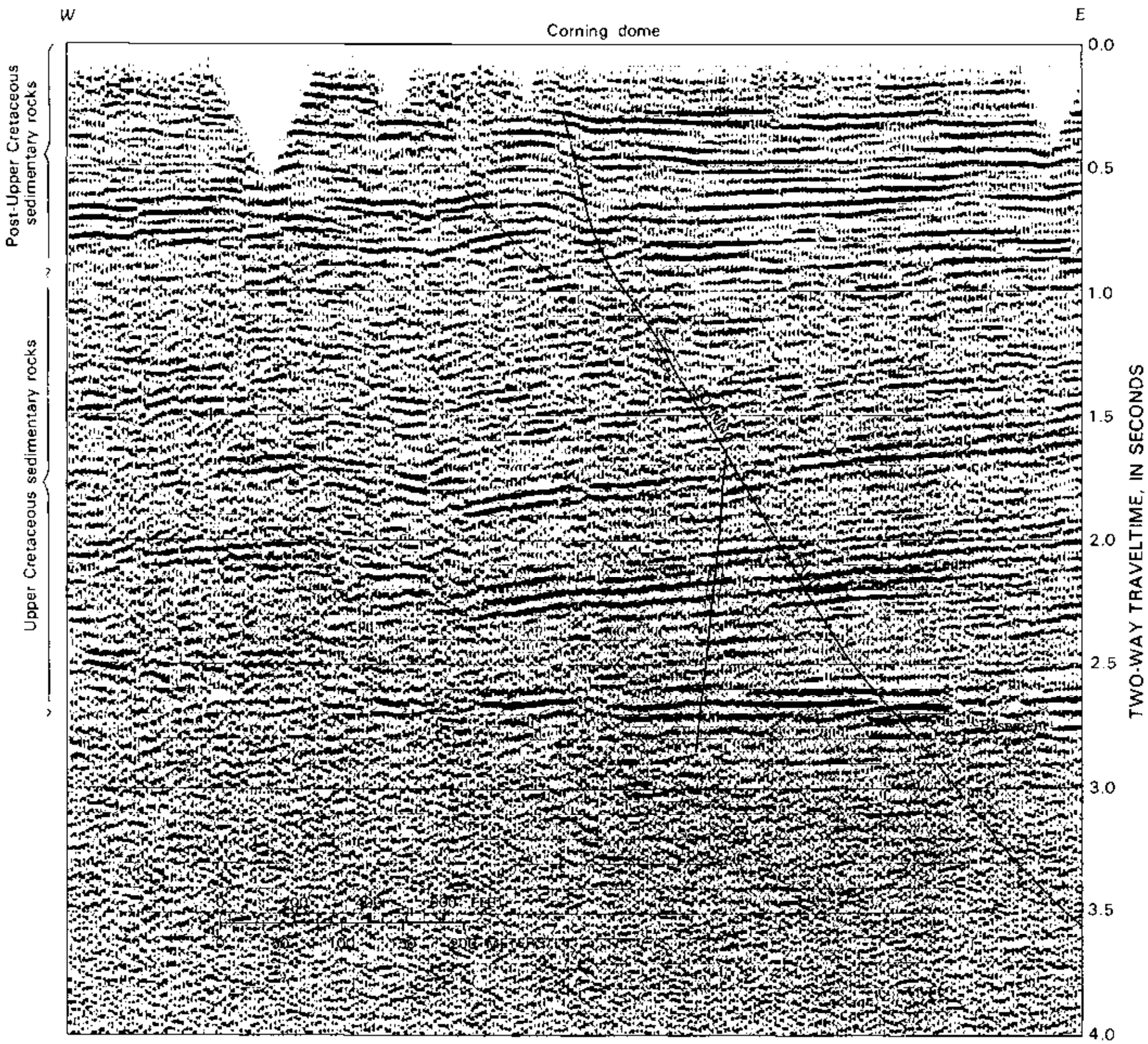


FIGURE 5.—Seismic-reflection profile, from Seisdata Services Inc., showing structural and generalized stratigraphic relations across Corning fault between Corning and Red Bluff, Calif.

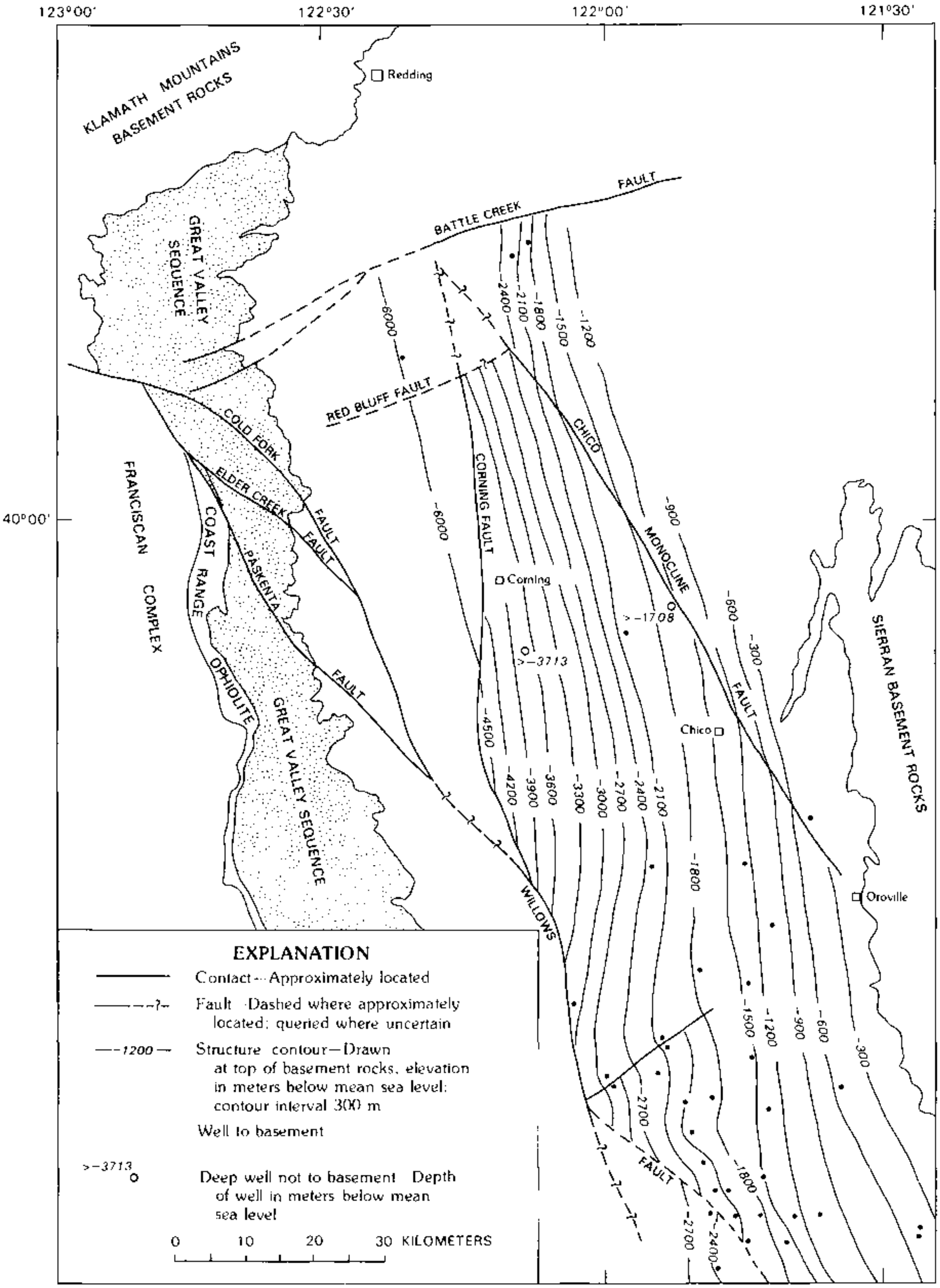


FIGURE 6.—Map of northern Sacramento Valley showing structure contours, drawn on top of basement rocks, used to estimate amount of vertical displacement of basement across Corning fault.

prior to eruption of the Nomlaki about 3.4 m.y. ago. We interpret the topographic low, reflected by the thicker basal part of the Tehama, to be the result of east-side-up movement on the Willows fault, prior to and possibly during, deposition of the lower part of the Tehama Formation. If this interpretation is correct, late Cenozoic movement on the Willows-Elder Creek fault system differs significantly, in style and amount of displacement, from the Cretaceous movement on the Elder Creek-Cold Fork-Paskenta fault system oulined by Jones and Irwin (1971).

Jones and Irwin (1971) inferred at least 96 km of left-lateral displacement of the Lower Cretaceous (Valanginian) strata along the combined Cold Fork-Elder Creek-Paskenta faults. They concluded that this deformation commenced shortly after deposition of the Valanginian strata and continued concurrently with deposition until at least the middle Late Cretaceous. Well-documented vertical displacement of Upper Cretaceous and overlying rocks on the Willows fault in the Willows-Beehive Bend gas field is not incompatible with left-lateral displacement on the Elder Creek fault system to the northwest, but it does indicate that the inferred lateral displacement was accompanied, or postdated by, a major component of east-side-up vertical movement. This vertical movement is consistent with the interpretation that the Elder Creek fault system represents tear faults in the upper plate of the Coast Range thrust (Jones and Irwin, 1971), along which the Klamath Mountains terrane moved upward and westward over the Coast Ranges province (fig. 2).

SOUTHEAST EXTENSION OF WILLOWS FAULT

Location of the Willows fault southeast of Sutter Buttes is not closely constrained by sparse well data along the eastern margin of the valley. No seismic-reflection profiles, that we are aware of, extend far enough east to cross the fault. However, wells in three widely spaced areas do extend far enough east from the deeper parts of the valley to cross the fault, and they provide the most direct evidence for the southeastern extension of the Willows fault. The first area we investigated extends southwest from near Marysville and passes through the Tisdale gas field (pl. 1, map A) just southeast of Sutter Buttes. A cross section (fig. 7) through wells in this area shows that the slope of the basement is significantly steeper east of the Willows fault (between wells 4 and 5, fig. 7), and we infer about 165 m of east-side-up displacement on the basement surface. Shale of the Eocene Capay Formation is recognizable in all of the electric logs in figure 7, and that unit shows about 100 m of displacement between wells 4 and 5. The base of continental deposits (nonmarine sedimentary rocks), which coincides generally with the base of fresh water in the valley, is difficult to identify in all the well logs of this section, but it does not appear to be offset between wells 3 and 5. The dip of the fault is not constrained in this section, and we have shown a steeply east-dipping reverse fault between wells 4 and 5, primarily because the pattern of offset in that area is so similar to that on the Willows fault to the northwest.

About 23 km southeast of the Tisdale gas field, a second line of wells extends from the Sacramento River near Knight's Landing northeastward toward Lincoln. Interest was directed initially to this line of wells because the outline of the Markley canyon, shown by Almgren (1978), is sharply deflected to the south in this area. A section through this line of wells is shown in figure 8. All of the sedimentary rocks in this part of the valley, except those in the Markley canyon, are offset up to the east between wells 3 and 4 (fig. 8). The amount of displacement appears to increase downward in the section from about 30 m at the base of the continental deposits to about 45 m in sandstone and shale sequences in the Upper Cretaceous rocks. Displacement of the basement is inferred to be about 150 m, but the depth to basement west of the Willows fault is not closely constrained by available well data. The most interesting aspect of the section is the marked asymmetry of the Markley canyon fill. Canyon development may have shifted progressively westward, to be localized immediately east of this part of the Willows fault, where the deepest part of the asymmetric canyon fill is located. This pattern of erosion and sedimentation suggests that late Oligocene and early Miocene movement on the Willows fault directly influenced the location and form of the Markley canyon.

The third line of wells we investigated extends from the Sacramento River near Clarksburg to the area east of Florin, where a series of low hills underlain by Pliocene continental deposits of the Laguna Formation rise above the surrounding Pleistocene alluvial deposits. A section through these wells is shown in figure 9. The electric log of the D. D. Feldman "Unit Plan No.1" well (sec. 8, T. 7 N., R. 6 E.); (No. 9, fig. 9) shows an obvious repeat in the Cretaceous rocks just above the basement. We interpret this repeat to represent east-side-up displacement on the Willows fault, which was intersected by the well at an elevation of –1,277 m. If this interpretation is correct, the basement surface is offset about 120 m. A similar offset is shown by Upper Cretaceous rocks.

West of the Willows fault (fig. 9), a steeply east-dipping normal fault, previously unreported, offsets the Capay Formation and older rocks down to the east about 153 m. This normal fault does not appear to offset the base of post-Eocene and younger nonmarine rocks, nor are these rocks offset by the Willows fault to the east. Offset of the basement between wells 5 and 6 (fig. 9) appears to be east side up and suggests early reverse movement on the east-dipping fault.

The location of the Willows fault southeast of Florin is

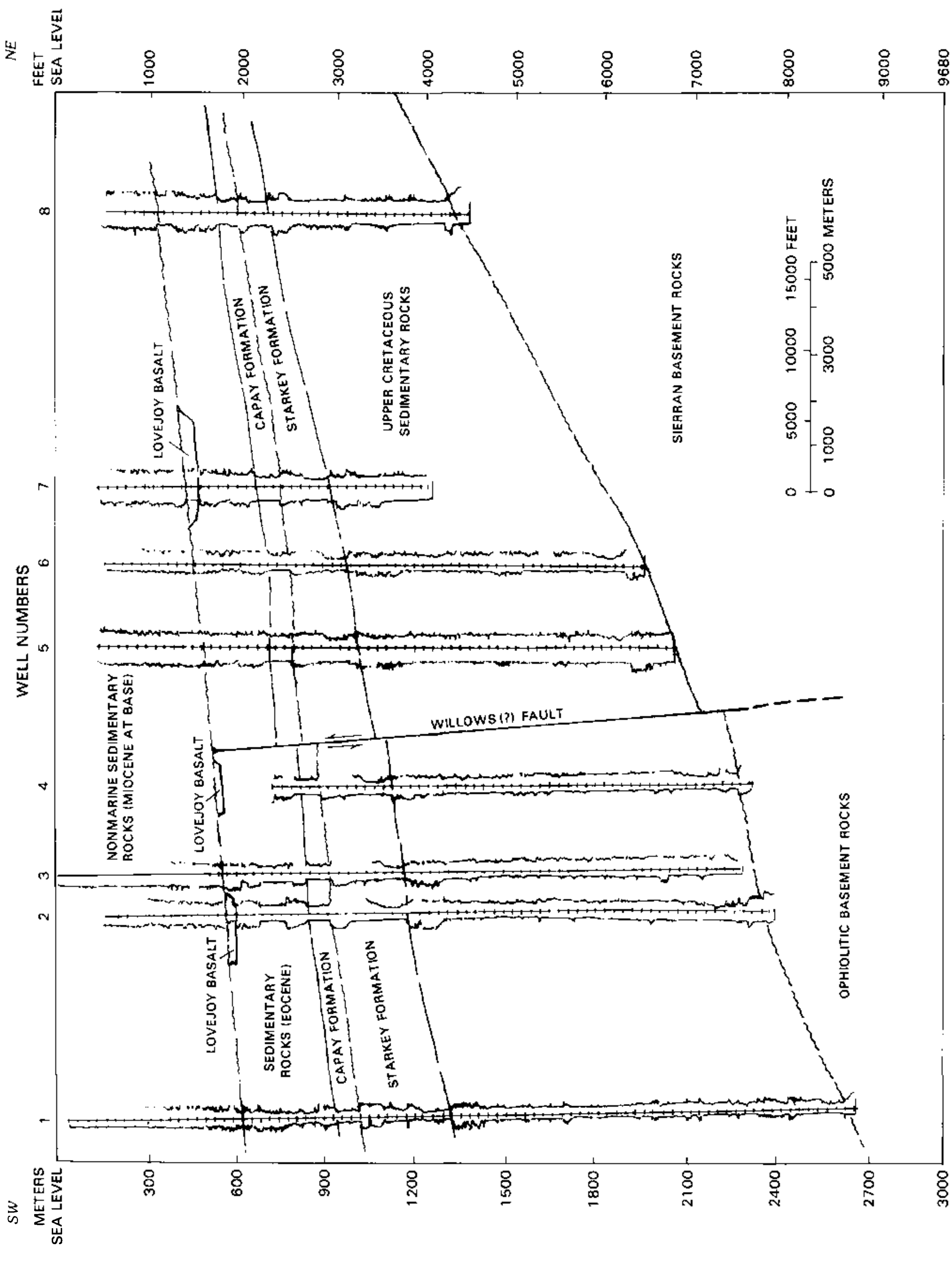


FIGURE 7.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault near Tisdale gas field southeast of Sutter Buttes, Calif. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

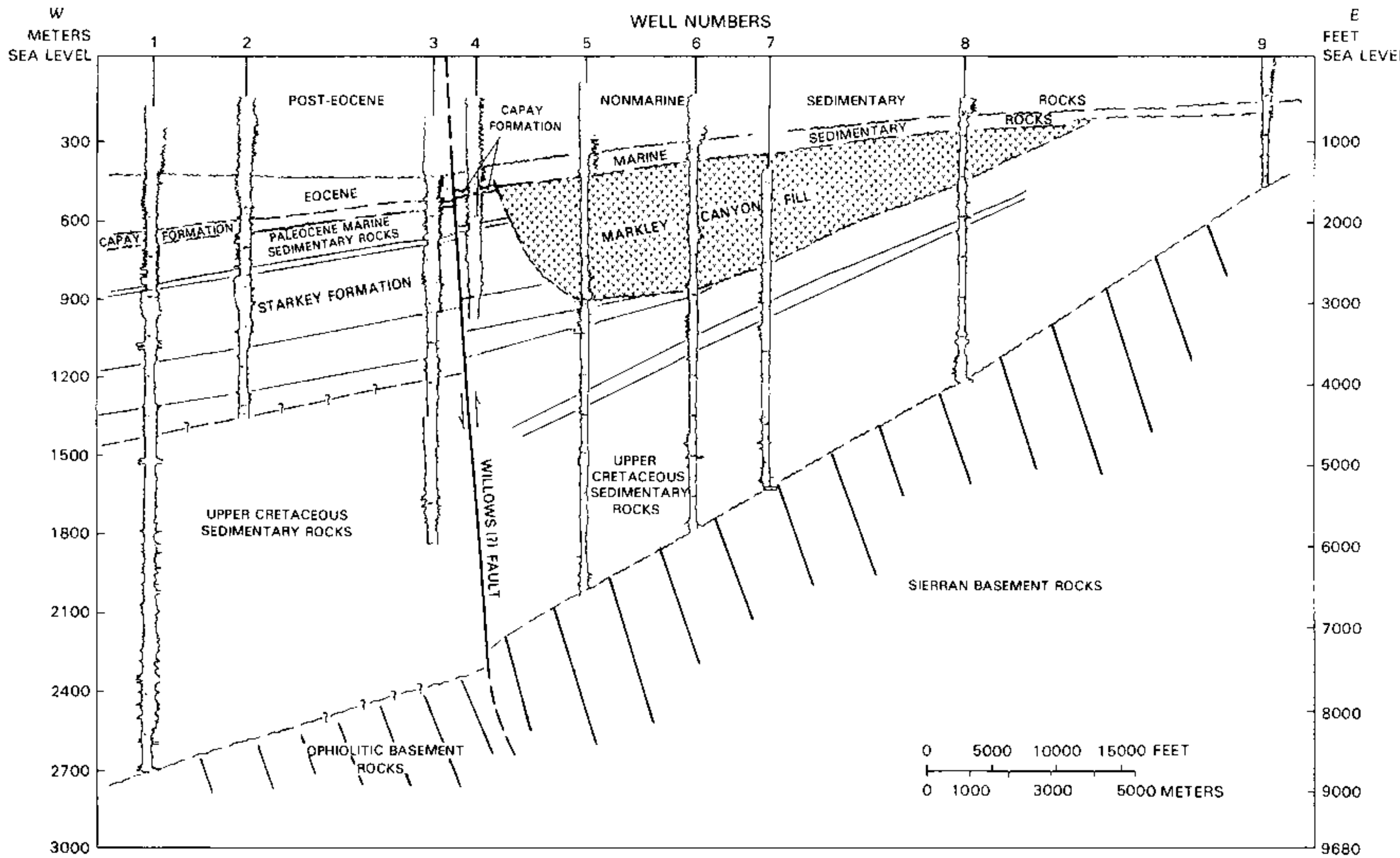


FIGURE 8.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault near Catlett-Nicolaus gas fields, Calif. Names of wells listed in appendix. Note asymmetry of Markley canyon fill (patterned) and absence of offset in post-Eocene continental deposits. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

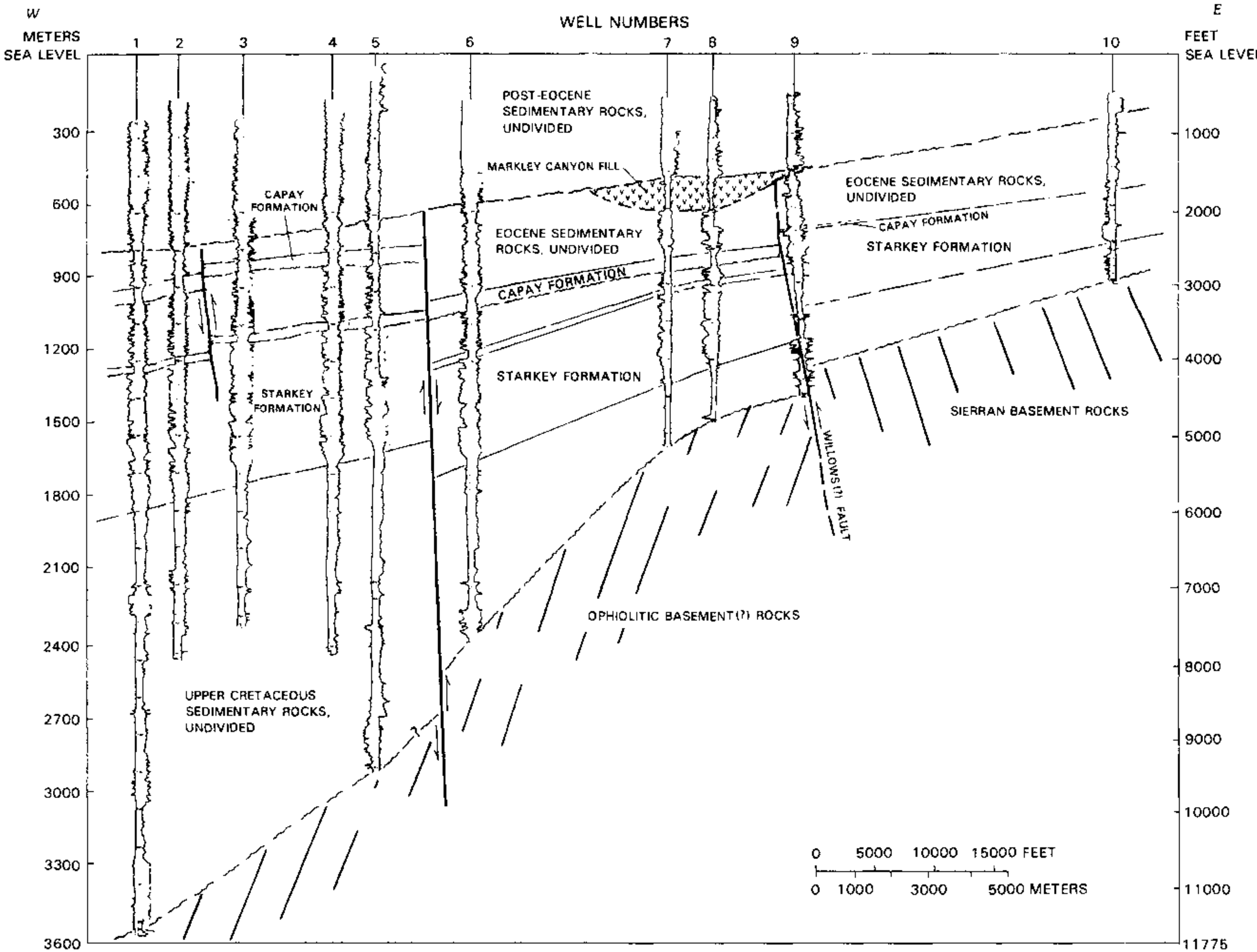


FIGURE 9.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault southeast of Florin, Calif. Names of wells listed in appendix. Note repeated electric-log pattern near bottom of well 9 and apparent early east-side-up displacement of basement by unnamed fault between wells 5 and 6, followed by east-side-down offset of Cretaceous and early Tertiary rocks. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological

uncertain. A section through several wells east and west of the Lodi gas field, shown in figure 10, indicates a minor deflection in the Capay Formation between wells 6 and 7, but the underlying Cretaceous rocks and the basement surface are not significantly offset in that area. The general east-side-up flexure of the Capay between wells 6 and 7 is the type of deformation that would be expected adjacent to the Willows fault, but the absence of offset in underlying units argues against the existence of the fault. Deformation expressed as fault movement north of Lodi may be expressed as gentle warping to the south.

STRUCTURES NORTHEAST OF THE WILLOWS FAULT

The Willows fault diagonally transects the Sacramento Valley from northwest to southeast and divides the region into two late Cenozoic structural provinces. To the northeast, on the upthrown block of the Willows fault, the present axis of the Sacramento Valley is underlain by the Los Molinos and Glenn synclines (pl. 1). These narrow synclines, coupled with the Corning domes to the west and the Chico monocline to the east, have tightly controlled the course of the Sacramento River and influenced alluvial deposition during the late Quaternary. This tectonic control of alluvial deposition has profoundly influenced land use, particularly in the northeastern part of the valley, where a narrow strip of cultivated land, shown near the top of figure 11, flanks the river and lies directly over the trace of the Los Molinos syncline. South of the constricting influence of the Corning domes and the Chico monocline, late Quaternary alluvial deposits spread laterally across much of the valley over the Glenn syncline, the axial trace of which controls the present course of the Sacramento River as far south as Glenn, Calif. (pl. 1). From Glenn to Colusa, the course of the river lies along the trace of the Willows fault.

From the vicinity of Willows southeast to the Sacramento Delta, the downthrown southwest block of the Willows fault is capped by Holocene basin deposits that flooded over the broad Zamora syncline (pl. 1), burying older deposits, to rest unconformably on Upper Cretaceous rocks north of the Dunnigan Hills. The following part of the report discusses specific structural features on the northeast block of the Willows fault.

SUTTER BUTTES

Sutter Buttes (fig. 11) is a prominent set of hills composed of late Cenozoic volcanic rocks that rise about 635 m above the floor of the Sacramento Valley 15 km northwest of Marysville. According to Williams and Curtis (1977), volcanism and accompanying deformation of the surrounding sedimentary rocks occurred between 2.4 and 1.4 m.y. ago and consisted of two phases. During the early phase of magma injection, Upper Cretaceous and Tertiary rocks were arched into a dome 13 km across, broken by normal and high-angle reverse faults, and rapidly eroded so that the Tertiary rocks were stripped from the core of the dome before the explosive phase of volcanism. Explosive volcanism produced the rampart beds of tuff and tuff breccia that form the peripheral deposits of the buttes (fig. 11).

Extensive drilling for natural gas located an elongate dome in the subsurface about 10 km west of Sutter Buttes. Williams and Curtis (1977) referred to this structure as the buried Colusa buttes, but because it lacks surface expression, we refer to it as the buried Colusa dome (fig. 12). In the buried Colusa dome, several wells (fig. 12) penetrated volcanic rocks similar in composition and age to those in the Sutter Buttes. These data led Williams and Curtis (1977) to conclude that the buried Colusa dome formed solely by forceful magma injection contemporaneous with magmatism at Sutter Buttes. We suggest, however, that magmatism may have been localized by movement on the Willows fault and possibly by movement on the Mesozoic tectonic boundary between ophiolitic and Sierran basement terranes which passes beneath the eastern margin of Sutter Buttes (fig. 12).

The orientation and movement patterns of structures at Sutter Buttes and the buried Colusa dome suggest that deformation occurred in a regional east-west compressive stress field. The distribution of structural features at Sutter Buttes is distinctively asymmetrical. Beds in the Upper Cretaceous rocks on the south and southeast sides of the buttes dip steeply away from the core. Locally, they are overturned. Beds on the north and northwest sides of the buttes generally dip gently away from the core. As shown in figure 12, folds and faults are more abundant on the eastern half of the buttes and the wavelength of folds is tighter there than on the west. In addition to the small normal faults that surround the core of the dome, the eastern half of the dome is cut by a prominent set of steeply inward-dipping, arcuate high-angle reverse faults. This pattern of structural features indicates that the core of Sutter Buttes was thrust eastward as it moved upward.

The northward elongation of the buried Colusa dome strongly suggests that it too was formed in an east-west compressive stress regime. In fact, the amplitude, wavelength, and axial extent of the buried Colusa dome are remarkably similar to folds that occur just east of the Willows fault farther north (pl. 1; fig. 3). Although Redwine (1972) projected the Willows fault southeastward across the buried Colusa dome, our analysis of subsurface data suggests that a fault, possibly the Willows fault or a splay fault related to it, may lie just west of the buried Colusa dome. We conclude that the buried Colusa dome formed partly by east-side-up drag on a high-angle reverse fault along its western margin and partly by magma in-

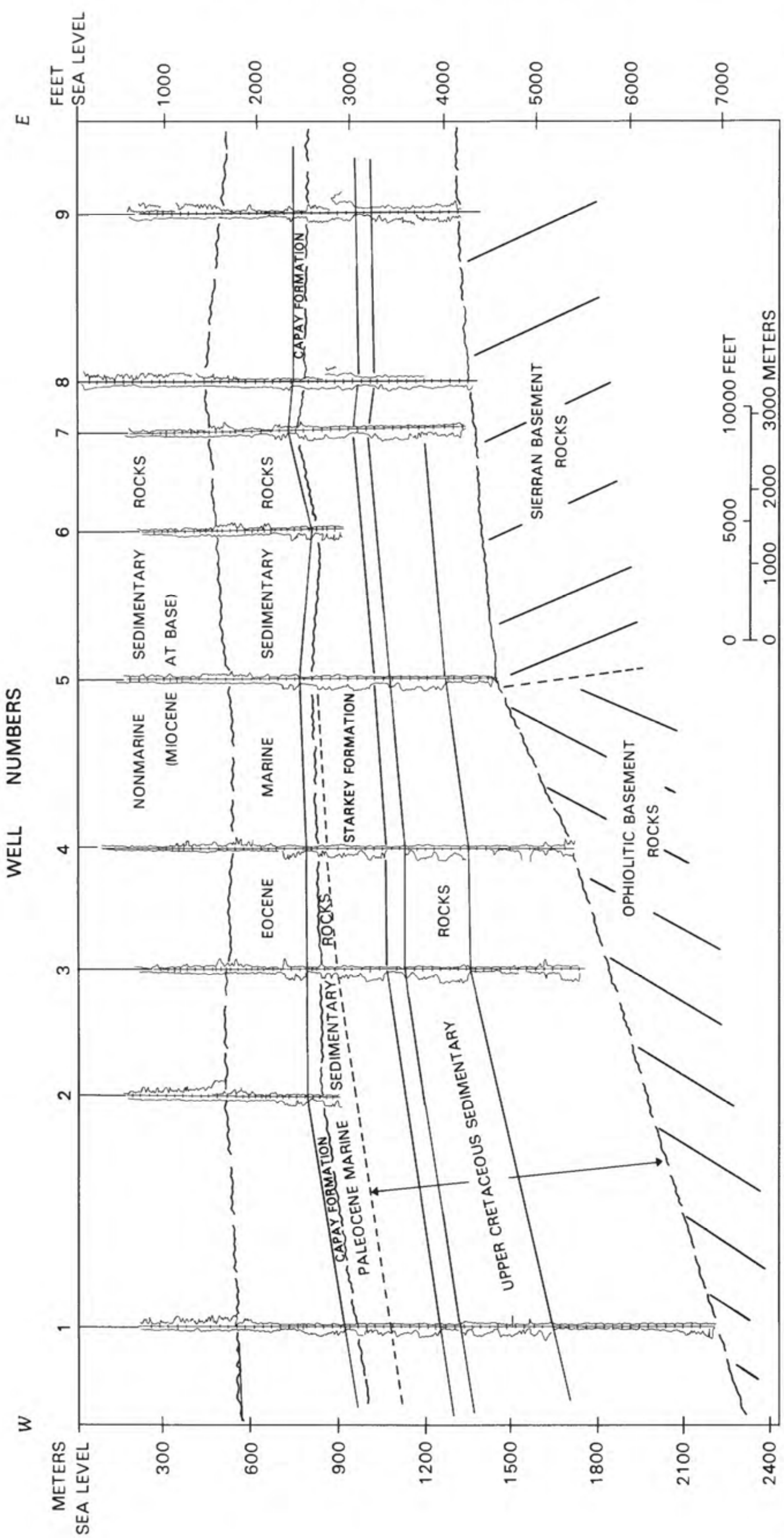


FIGURE 10.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault (approximately follows trace of well 5) in area of the Lodi and Galt gas fields, Calif. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

jection that was localized by movement on that fault.

The pattern of radial normal faults around the core of Sutter Buttes, flanked by reverse faulting to the east and west, assuming that the Willows fault was involved in the tectonism, is the type of deformation found by Withjack and Scheiner (1982) in their modelling experiments of doming in a compressive stress field. Although it is difficult to unequivocally separate magmatic doming from regional compressive deformation in the Sutter Buttes area, supporting evidence for the regional east-west compressive stress field is found in the Chico monocline about 40 km to the north.

FIGURE 11.—U.S. Air Force high-altitude oblique aerial photograph showing northern Sacramento Valley viewed to the north from vicinity of Sutter Buttes (center foreground), a late Pliocene and early Pleistocene volcanic center, approximately 16 km in diameter. Dark core of buttes composed primarily of andesite surrounded by lighter colored volcaniclastic deposits that form peripheral rampart beds of Williams and Curtis (1977). Narrow strip of cultivated land (dark) along Sacramento River (SR) between Corning domes (CD) and Chico monocline (CM) is surface expression of Los Molinos syncline (pl. 1). Oroville dam (OD) located near north end of Cleveland Hills faults where ground rupture occurred during August 1, 1975, Oroville earthquake.

CHICO MONOCLINE

The Chico monocline (fig. 13) is a northwest-trending, southwest-facing flexure that bounds the northeast side of the Sacramento Valley between Chico and Red Bluff. East of the monocline, Pliocene volcanic rocks of the Tuscan Formation dip less than 5° SW., but bedding steepens to 20° or more along the monoclinal flexure where the Tuscan dips beneath Quaternary deposits of the valley. The trace of the monocline is characterized by a complex surface pattern of anastomosing fault strands

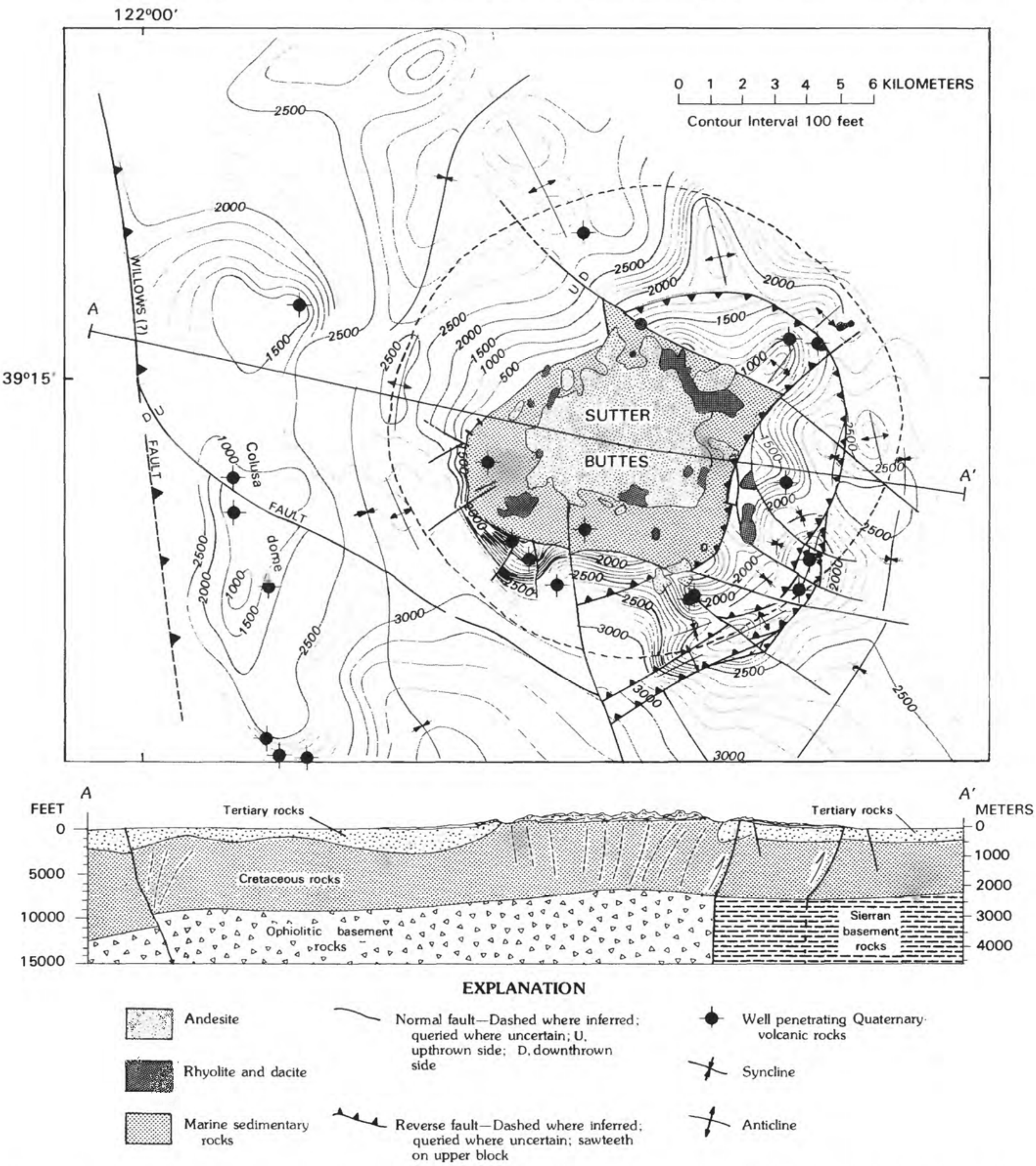


FIGURE 12.—Structure contour map of area around Sutter Buttes, modified from Williams and Curtis (1977, fig. 11) with data from Redwine (1972) and from our examination of electric logs in area of buried Colusa dome. Structure contours in feet; datum is top of the Kione sand of local usage (Williams and Curtis, 1977). Dashed circle on map marks approximate outer limit of rampart beds on valley floor; thin dashed lines on section represent schematic paths of magma injection.

FIGURE 13.—Composite of two U.S. Air Force high-altitude oblique aerial photographs showing pronounced linear trace of Chico monocline (CM, upper right to lower left), broad alluvial fan west of Chico monocline capped by Red Bluff Formation (RB, gray, uncultivated grazing land), and dissected topography of Tuscan Formation (TF) to east. DC, Deer Creek; CD, north Corning dome. Sacramento River (SR) follows trace of Los Molinos syncline (LMS) between north Corning dome and alluvial fan to east.

that show both west- and east-side-down displacements of small magnitude (Harwood and others, 1981).

Structure contours drawn on top of the Cretaceous rocks in the vicinity of the monocline indicate clearly that the Cretaceous strata are flexed and faulted by a major northwest-trending fault at depth beneath the surface trace of the monocline (pl. 1). The best control on the amount of displacement on the master fault beneath the Chico monocline comes from a line of wells that extends generally westward from the Exxon "C. C. Baccala No. 1" well (No. 4, fig. 14), which was drilled just west of the monocline about 18 km northwest of Chico. Although the Baccala well did not reach basement, it bottomed in Upper Cretaceous conglomerate at a depth of −1,700 m and provides a minimum elevation on the basement immediately west of the monocline when used in conjunction with the Pacific Western "Cana No. 1" well (No. 2, fig. 14) that reached serpentine at a depth of −2,100 m about 9 km to the west. Although no wells have been drilled east of the monocline, some control on the elevation and dip of the unconformities at the top and base of the Upper Cretaceous rocks is provided by exposures of these surfaces in several deep canyons to the east. When the trend of the basement surface at these exposures is projected westward, to pass beneath the bottom of the Baccala well, a minimum east-side-up offset of 365 m in the basement rocks is indicated on the fault beneath the monocline (fig. 14). The dip of this major fault cannot be determined directly from surface exposures or subsurface well data, but we show it as a steeply east-dipping reverse fault, because gravity and magnetic data (Griscom, 1973; Cady, 1975; Roberts and others, 1981) indicate that the relatively dense and magnetic basement beneath the northern part of valley extends eastward beneath the Sierran basement exposed east of the monocline. In the Sierran foothills southeast of Oroville, steep east dips are also commonly found in surface exposures of faults that may be the southeastward continuation of the fault beneath the monocline.

From available geophysical evidence, it appears that the fault beneath the monocline is a major tectonic boundary, with a long and complex tectonic history, along which the Sierran basement to the east was juxtaposed against highly magnetic, dense ophiolitic basement to the west (Cady, 1975; Griscom, 1973). These basement terranes were tectonically juxtaposed prior to deposition of the Upper Cretaceous strata. If this interpretation is correct, the fault beneath the Chico monocline may represent a part of the upper-slope discontinuity of Karig and Sharman (1975) that marks the boundary between basement of the late Mesozoic forearc basin to the west and that of the magmatic arc complex to the east. The Chico monocline, in that case, would be a structure inherited from the upper-slope discontinuity, possibly when that major tectonic break was reactivated by late Cenozoic subduction north of the migrating Mendocino triple junction.

The Chico monocline is clearly a late Cenozoic tectonic feature. It formed after deposition of the Ishi Tuff Member of the Tuscan Formation, about 2.6 m.y. ago and prior to the eruption of the olivine basalt of Deer Creek 1.09 m.y. ago (Harwood and others, 1981). Late Cenozoic displacement on the Chico monocline fault has been predominantly east side up, with an apparent component of left-lateral movement that may have contributed to the formation of the Salt Creek, Tuscan Springs and Sevenmile domes at the north end of the monocline and possibly influenced the northeast-trending Inks Creek fold system and Battle Creek fault zone farther northwest.

There is some indication that the Chico monocline fault may be active. The olivine basalt of Deer Creek is offset, but the amount of offset is small. Similarly, a few faults along the monocline show scarps about 1 m in height in the surface of the Tuscan Formation (Harwood and others, 1981). These observations indicate that movement has taken place on the monocline fault system within the past million years. In their study of regional seismicity after the Oroville earthquake, Marks and Lindh (1978)

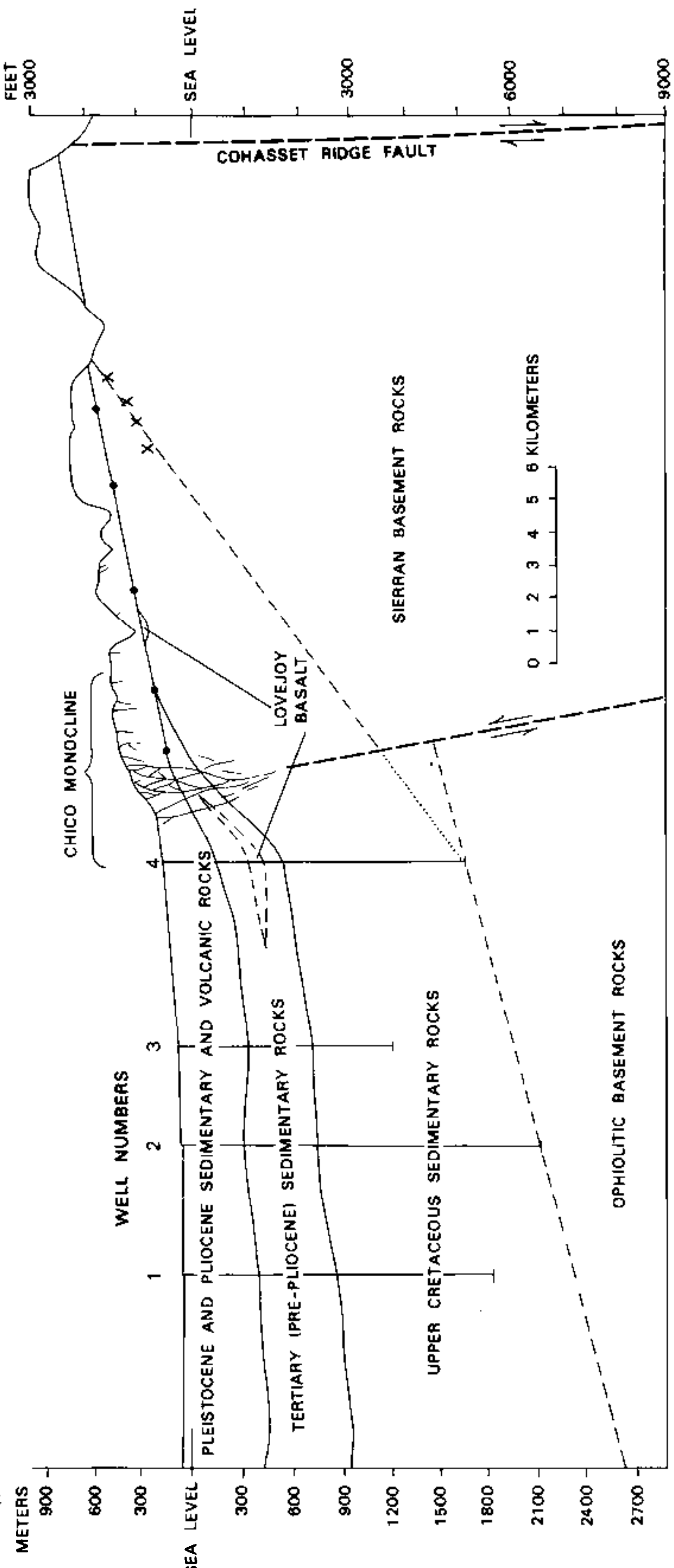


FIGURE 14.—Cross section across Chico monocline about half way between Chico and Red Bluff, Calif., showing offset of basement terranes. Dots indicate unconformity at base of Tuscan Formation, as projected into line of section; x's indicate unconformity at base of Upper Cretaceous rocks, as projected into line of section. Names of wells listed in appendix.

identified two events west of the Oroville aftershock zone at a depth of 40 km, significantly below the main cluster of aftershocks associated with the Oroville earthquake. We interpret those deep events to have occurred on the

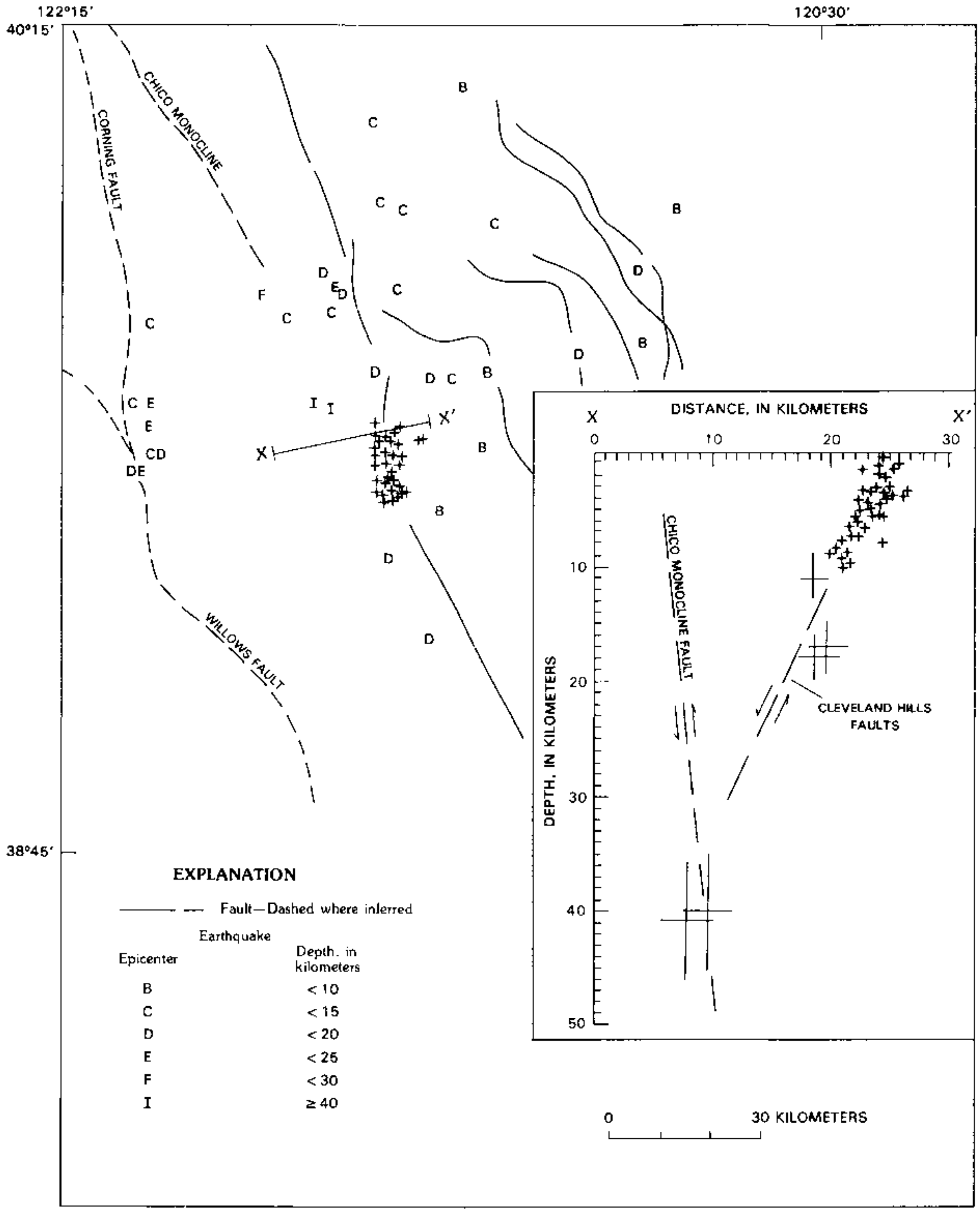


FIGURE 15.—Map and section showing locations of Oroville earthquake aftershocks (crosses on section) in relation to Cleveland Hills faults and Chico monocline (modified from Marks and Lindh, 1978). Earthquakes labeled I on map (largest crosses on section) at a depth of about 40 km are interpreted to have occurred on Chico monocline fault.

basement fault beneath the Chico monocline and not on the Cleveland Hills faults, where most of the aftershock events were located (fig.15). The steeply east-dipping normal fault, shown east of the Chico monocline on figure 15, is one of several short, north- and north-northwest-trending normal faults that extend along the northern foothills of the Sierra Nevada (pl. 1). This normal fault is probably part of the fault system on which the August 1, 1975, Oroville earthquake occurred.

BATTLE CREEK FAULT ZONE

The Battle Creek fault zone strikes east-northeast across the Sacramento Valley between Red Bluff and Redding, nearly at right angles to the trend of the Chico monocline. East of the Sacramento River, the Battle Creek fault zone is marked by a pronounced south-facing escarpment, shown in figure 16, that extends from the river northeastward toward Lassen Peak for a distance of 32 km. Fault strands within this part of the fault zone dip steeply southeast and show predominantly south-side-down, normal fault movement (Harwood and others, 1980; Helley and others, 1981). Vertical displacement on the fault zone increases from about 45 m just east of the Sacramento River to 330 m at Black Butte (fig. 1) and to about 440 m north of Manton. A small component of right-lateral strike-slip movement is suggested by fractures on some of the fault strands, but the exact amount of lateral displacement is not known.

West of the Sacramento River, the valleys of Cottonwood Creek and its south fork are probably controlled in part by the Battle Creek fault system, but modern stream activity and agricultural practices obscure any young traces of the faults east of the South Fork of Cottonwood Creek (pl. 1). At the South Fork of Cottonwood Creek and along Red Bank Creek, late Quaternary terraces show evidence of young faulting (Helley and others, 1981). To the west-southwest, the faults in the terrace deposits merge into previously mapped faults in the Red Bluff and Tehama Formations, and, on strike, they appear to merge with tear faults in the upper plate of the Coast Range thrust mapped by Bailey and Jones (1973).

FIGURE 16.—Photograph of Battle Creek fault scarp (BC) capped by basaltic cinder cone of Black Butte. View to northeast along Highway 36 and across rolling grassy plains underlain by volcanic fanglomerate correlated with the Red Bluff Formation.

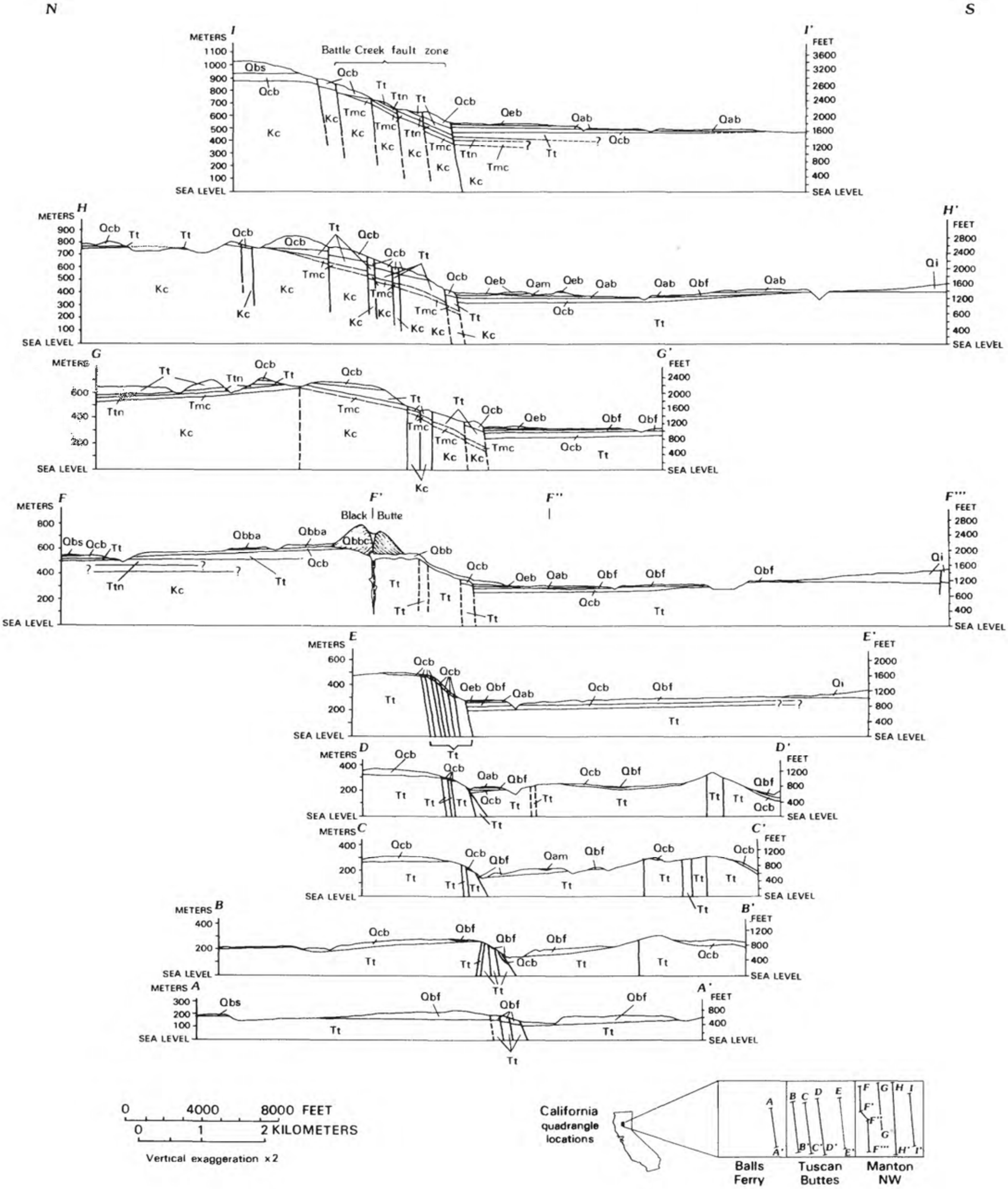
The orientation and distribution of faults in the Battle Creek fault zone east of the Sacramento River are shown in figure 17. Section *A-A′* is located 2.4 km east of the Sacramento River and shows relatively little offset of the fanglomerate that caps the Tuscan Formation. As the fault zone extends eastward, offset on the various Pliocene and Pleistocene units and the height of the fault scarp increases. From near the Sacramento River east to Black Butte (sections *A-A′* through *F-F′*, fig. 17), the fault strands are closely grouped along the fault scarp, but east of Black Butte (sections *G-G′* through *I-I′*, fig. 17) the fault strands are more widely spaced. In map view, the eastern fault strands veer northwestward and appear to die out a short distance north of the escarpment (Harwood and others, 1980).

Several clusters of small-magnitude earthquakes were reported along the eastern third of the Battle Creek fault zone, generally east of Black Butte (Bolt, 1979). Since 1980 the California seismic net of the U.S. Geological Survey has recorded several small-magnitude earthquakes (J. Eaton, oral commun., 1982) that lie approximately along the Battle Creek fault zone and extend west nearly to the Sacramento River.

Coarse volcanic fanglomerate, correlated here with the Red Bluff Formation by soil stratigraphy and geomorphic surface, is offset by the Battle Creek fault zone east of the Sacramento River and dates the major movement as younger than 1.09 m.y. The Rockland ash bed (referred to as the ash of Mount Maidu by Helley and others, 1981) appears to have been partly channeled by the Battle Creek fault scarp, suggesting that the faulting occurred prior to about 0.45 m.y. ago, the age of the Rockland ash bed (Meyer and others, 1980).

INKS CREEK FOLD SYSTEM

A set of northeast-trending folds, referred to as the Inks Creek fold system by Helley and others (1981), deforms the rocks south of the Battle Creek fault zone and structurally controls the major loops in the Sacramento River at Jelly School and the nearby Table Mountain (pl. 1; figs. 1, 18). The axial trace of the major syncline in the fold set passes through Table Mountain and extends northeastward, nearly coincident with Inks Creek. The complementary anticline to the north arches the volcanic fanglomerate, which is correlated with the Red Bluff Formation, and the underlying basalt of Coleman Forebay (Helley and others, 1981), exposing strata of the uppermost part of the Tuscan Formation northeast of Jelly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S
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METERS
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Battle Creek fault zone
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Vertical exaggeration x2
California quadrangle locations
Balls Ferry
Tuscan Buttes
Manton NW

School. Axial surfaces of the folds are vertical, and fold axes plunge 20°–35° SW. Axial traces of the folds change strike to the northeast so that the anticlinal trace merges with the trend of the Battle Creek fault zone and apparently dies out along the fault to the east-northeast.

West of the Sacramento River, the Inks Creek fold system is expressed as a broad area of uplift known as the Hooker dome (fig. 18). This structure, which has profoundly influenced drainage patterns in the area, particularly along Hooker Creek and Blue Tent Creek (fig. 18), is underlain by the Tehama Formation capped by a few scattered erosional remnants of the Red Bluff Formation.

The Inks Creek fold system is clearly reflected in the structure contours drawn on top of the Cretaceous rocks, which show a closure of about 485 m over the anticline (pl. 1). Although only a few wells in this area reach basement, the elevation of the basement in two wells drilled on the anticline of the Inks Creek fold system is higher than the total depth of some wells to the west that bottomed in Upper Cretaceous rocks. These data indicate that the basement was deformed, along with the cover rocks, during formation of the Inks Creek fold system. They also strongly suggest that the folds shown by the structure contours on plate 1 involve the basement of the valley rather than deformation on a decollement or a series of detachment thrusts in the cover rocks.

The fact that the anticlinal trace of the Inks Creek fold system merges with the Battle Creek fault zone suggests a genetic relation between these major structures. If this interpretation is correct, evidence for the age of the Inks Creek fold system provides data for the age of movement on the Battle Creek fault zone. At Round Mountain, about 3 km southwest of Jelly School, the Rockland ash bed rests unconformably on the eroded western contact of the Red Bluff Formation at an elevation of 160 m. We assume that the ash was deposited in an ancestral channel of the Sacramento River, which apparently formed a large westward bend at that time extending from Bloody Island on the north to the vicinity of Bend on the south (fig. 18). Uplift and erosion of the Red Bluff Formation, which was deposited between 0.45 and 1.09 m.y. ago, had begun

EXPLANATION

- Qi — BASALTIC ROCKS OF INSKIP HILL VOLCANIC CENTER (QUATERNARY)--Undifferentiated basalt of Inskip Hill
- BASALTIC ROCKS OF BLACK BUTTE VOLCANIC CENTER (QUATERNARY)--Consist of:
  - Qbbc — Cinder-cone deposits
  - Qbba — Cinder-blanket deposits
  - Qbb — Basalt flow of Black Butte
- Qbs — BASALT OF SHINGLETOWN RIDGE (QUATERNARY)
- Qeb — BASALT OF EAGLE CANYON (QUATERNARY)
- Qab — HYPERSTHENE ANDESITE OF BROKEOFF MOUNTAIN (QUATERNARY)
- Qam — ASH OF MOUNT MAIDU (QUATERNARY)--Equivalent to the Rockland ash bed of Sarna-Wojcicki and others (1985)
- Qbf — ALLUVIAL FAN DEPOSITS OF BATTLE CREEK (QUATERNARY)
- Qcb — BASALT OF COLEMAN FOREBAY (QUATERNARY)
- Tt — TUSCAN FORMATION, UNDIVIDED (PLIOCENE)--Locally divided into:
  - Ttn — Nomlaki Tuff Member
- Tmc — MONTGOMERY CREEK FORMATION (EOCENE)
- Kc — CHICO FORMATION (UPPER CRETACEOUS)

FIGURE 17.—Geologic cross sections showing statigraphic and structural relations along Battle Creek fault zone. Note eastward increase in height of fault scarp and amount of offset of geologic units from section A-A′ to section I-I′. Geologic units from Helley and others (1981).

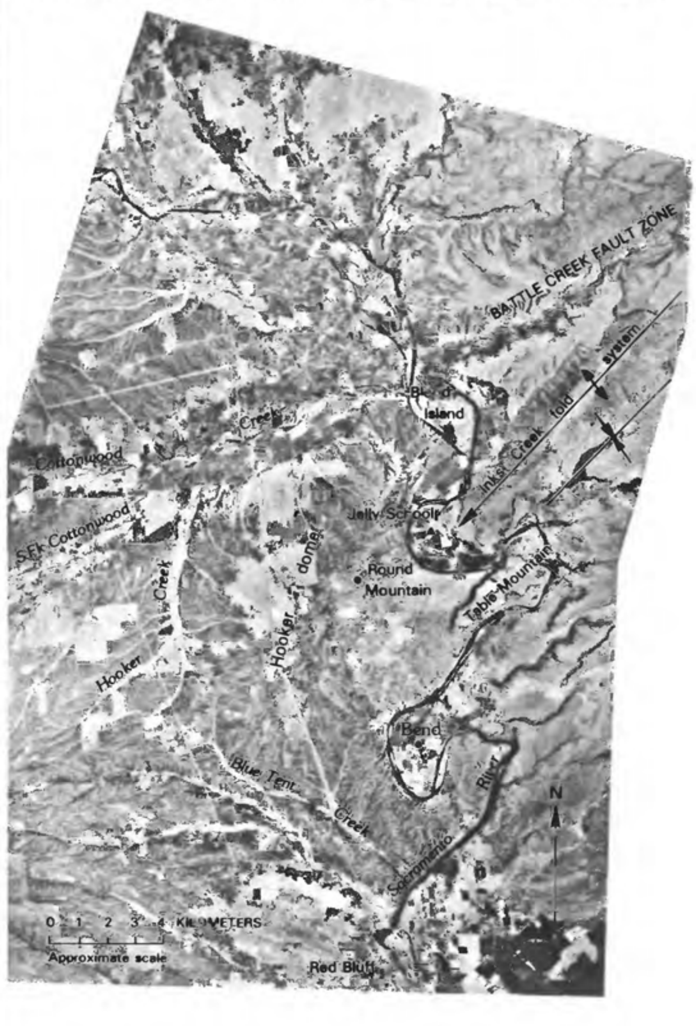


FIGURE 18.—Composite of two U.S. Air Force high-altitude vertical aerial photographs showing topographic expression of Inks Creek fold system (axial traces), Hooker dome, and Battle Creek fault zone.

prior to deposition of the ash. In contrast to the occurrence of the ash at Round Mountain, alluvial deposits of the lower part of the Riverbank Formation are found at an elevation of 120 m in this region, and they flank the present sinuous course of the Sacramento River through the structurally controlled loops of the river at Jelly School and Table Mountain. Clearly, the Sacramento River was forced into its tortuous course around the Inks Creek fold system by early Riverbank time. We conclude, therefore, that the Inks Creek fold system and at least some of the displacement on the Battle Creek fault zone developed in the timespan between 0.45 m.y., the age of the ash, and about 0.4 m.y. ago, the age of the lower part of the Riverbank Formation (Marchand and Allwardt, 1981).

SALT CREEK, TUSCAN SPRINGS, AND SEVENMILE DOMES

Small areas of Upper Cretaceous marine rocks are exposed beneath the Pliocene Tuscan Formation in Salt Creek, at Tuscan Springs, and in Sevenmile Creek between the north end of the Chico monocline and the Inks Creek fold system (pl. 1). In each area, beds in the Tuscan dip outward, away from the Upper Cretaceous rocks, and define three small domes, shown on plate 1 as the Salt Creek, Tuscan Springs, and Sevenmile domes.

The long axes of the domes trend north-northeast and plunge 15°–25° NE. and SW. Cold sulfurous springs are present in the Salt Creek and Tuscan Springs domes, and olivine basalt rests unconformably on steeply northwest-dipping Upper Cretaceous rocks in the core of Sevenmile dome. The olivine basalt was extruded from a north-trending fissure after the Tuscan Formation was domed and erosion had exposed the Upper Cretaceous rocks.

The age of the olivine basalt is unknown, but it probably is a few tens of thousands of years old, at most, and is roughly coeval with similar basalt flows and cinder cones found at Inskip Hill (pl. 1) and Black Butte along the Battle Creek fault zone. The domes probably formed during the same phase of late Quaternary deformation about 0.4–0.45 m.y. ago that produced the Inks Creek fold system and the Battle Creek fault zone, and they are thus younger than the Chico monocline.

RED BLUFF FAULT

The Red Bluff fault is a subsurface structure that extends southwest of Red Bluff for at least 25 km. West of Red Bluff, there is no surface feature associated unequivocally with the fault, and its location on plate 1 is taken from Jennings' (1977) geologic map of California. Apparently Jennings included the fault on that map on the basis of seismic-reflection data obtained from private industry (Oliver and Griscom, 1980). We have not seen that data or any other seismic profiles that might cross the fault. Griscom (1973) inferred the existence of a major northeast-trending fault in the area from magnetic data.

East of Red Bluff, structure contours on top of the Cretaceous rocks outline a major anticline, the broad crest of which lies beneath the Salt Creek, Tuscan Springs, and Sevenmile domes. The axial trace of this anticline roughly coincides with the east-northeast projection of the Red Bluff fault, but there is no indication that the Tuscan Formation is faulted at the surface along the N. 70° E. trend. The southeast limb of the anticline may be faulted at depth, but surface and subsurface data are too sparse to either prove or refute that structural possibility. Between Tuscan Springs and the Humble "Cone Ranch No. 1" well (sec. 20, T. 27 N., R. 2 W.) to the south, the top of the Cretaceous sequence drops about 1,433 m over a distance of less than 8 km. The lower elevation is due to warping and faulting on the Chico monocline fault, as well as to folding and possible faulting along the northeast projection of the Red Bluff fault.

From our reinterpretation of a north-south section along the Sacramento River near Red Bluff given by Redwine (1972, section *F-F'*), the base of the Tehama Formation could be offset, down to the south, by as much as 141 m across the Red Bluff fault just east of Red Bluff. Because of the lack of northeast-trending surface faulting in the Tuscan to the east, however, it seems unlikely that all of that differential elevation is due to fault displacement; much of it may be related to folding over a fault at depth.

FAULTS SOUTH OF INSKIP HILL

The northwest-trending arcuate faults that are shown south of Inskip Hill (pl. 1) are a gross simplification of the faults and fractures found in that area. In detail, the Tuscan Formation is laced with a dense network of short anastomosing faults along which thin lines of shrubs and trees grow (fig. 19). The amount of offset on a single fault is small, generally a few meters or less, and there appears to be no significant cumulative offset in the Tuscan Formation across the fractured area.

The arcuate pattern of faults is concave toward the area of Mineral, to the east, where Wilson (1961) identified a major volcanic center that he called Mount Maidu. It seems reasonably certain that the fracture pattern is related to volcanic-tectonic activity in the Lassen area, but whether it is associated with Mount Maidu or some other volcanic center is uncertain.

STRUCTURES SOUTHWEST OF THE WILLOWS FAULT

With the exception of the buried Colusa dome, the subsurface structure of the valley southeast of the Willows fault to the Sacramento Delta is dominated by the Zamora syncline. South of buried Colusa dome, the Zamora syncline is asymmetrical and has a broad, gently west-dipping east limb that extends to the Sierran foothills and a steeply dipping west limb that is warped by southeast-plunging folds. North of the buried Colusa dome, the axial trace of the Zamora syncline intersects the Willows fault, and the top of the Upper Cretaceous rocks defines a generally east-dipping homocline. The following sections discuss structural features west of the axial trace of the Zamora syncline.

CAPAY VALLEY-CAPAY HILLS AREA

Cache Creek drains east from Clear Lake and enters the Sacramento Valley west of Woodland, through the tectonically controlled depression of Capay Valley. On the west, Capay Valley is flanked by the eastern slope of the Coast Ranges that contain a remnant of Eocene marine sandstone and shale of the Capay Formation (Redwine, 1972) resting unconformably on Upper Cretaceous marine rocks (Kirby, 1943a). Beds in the Capay and underlying rocks dip 25°-55° E. The Capay Hills, previously known as the Rumsey Hills (Kirby, 1943b), lie immediately east of Capay Valley and are underlain by the same Upper Cretaceous rocks exposed to the west. Here, however, the Cretaceous rocks lie in the core of a faulted southeast-plunging anticline, shown by structure contours on plate 1. They are unconformably overlain by nonmarine sandstone and shale of the Pliocene Tehama Formation. The Eocene Capay Formation is not present in the Capay Hills or in the Capay Valley, where scattered subsurface and surface data indicate that the Tehama rests unconformably on Upper Cretaceous rocks.

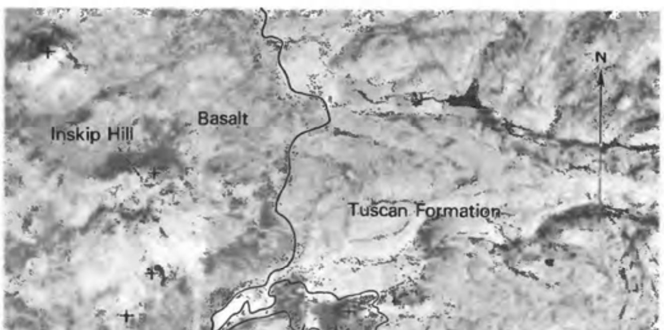


FIGURE 19.—Low-altitude vertical aerial photograph (U.S. Geological Survey) showing arcuate fault pattern (dashes) and cinder cones (crosses) south of Inskip Hill. Gray incised plains are underlain by the Tuscan Formation; thin dark lines are concentrations of brush and trees growing along fault traces.

On the floor of Capay Valley, the Tehama and older rocks have been eroded, and old stream channels have been filled with a variety of Quaternary alluvial deposits. Alluvial deposits of the upper part of the Modesto Formation indicate that Cache Creek entered the Sacramento Valley through a channel cut in the Tehama Formation near the west boundary of Capay Valley in late Wisconsin time. During the past 12,000 years the course of Cache Creek has shifted eastward so that the creek now exits Capay Valley through a sharp gorge cut into the relatively resistant Upper Cretaceous rocks at the southern end of Capay Hills. The shift in the course of Cache Creek and the surface and subsurface data that show faulting in the Tehama Formation provide strong evidence for late Cenozoic tectonism in Capay Valley.

Along the west flank of the Capay Hills, Kirby (1943b) mapped a northwest-trending, east-dipping thrust, the Sweitzer fault, and a lower ancilliary thrust, the Eisner fault; both faults place Upper Cretaceous rocks in contact with the Tehama. Wagner and Saucedo (1984) have reinterpreted the Sweitzer and Eisner faults as west-dipping normal faults. Their interpretation of the Sweitzer fault is supported by subsurface data at the south end of Capay Hills, where the contact between the Forbes and Guinda Formations of Kirby (1943a) is downfaulted about 50 m on the west (fig. 20, wells 3 and 4). Compared to other faults in the area, the Sweitzer fault appears to have played a relatively minor part in the structural evolution of the Capay Valley and Capay Hills.

West of the Sweitzer fault, the contact between the Forbes and Guinda Formations was reported at an elevation of about 219 m beneath the Capay Valley (fig. 20, well 2). That contact is displaced about 610 m up to the west along the northwest-trending, steeply east-dipping East Valley fault (fig. 20). Along the west margin of Capay Valley, the contact between Upper Cretaceous rocks and the Tehama Formation is down faulted about

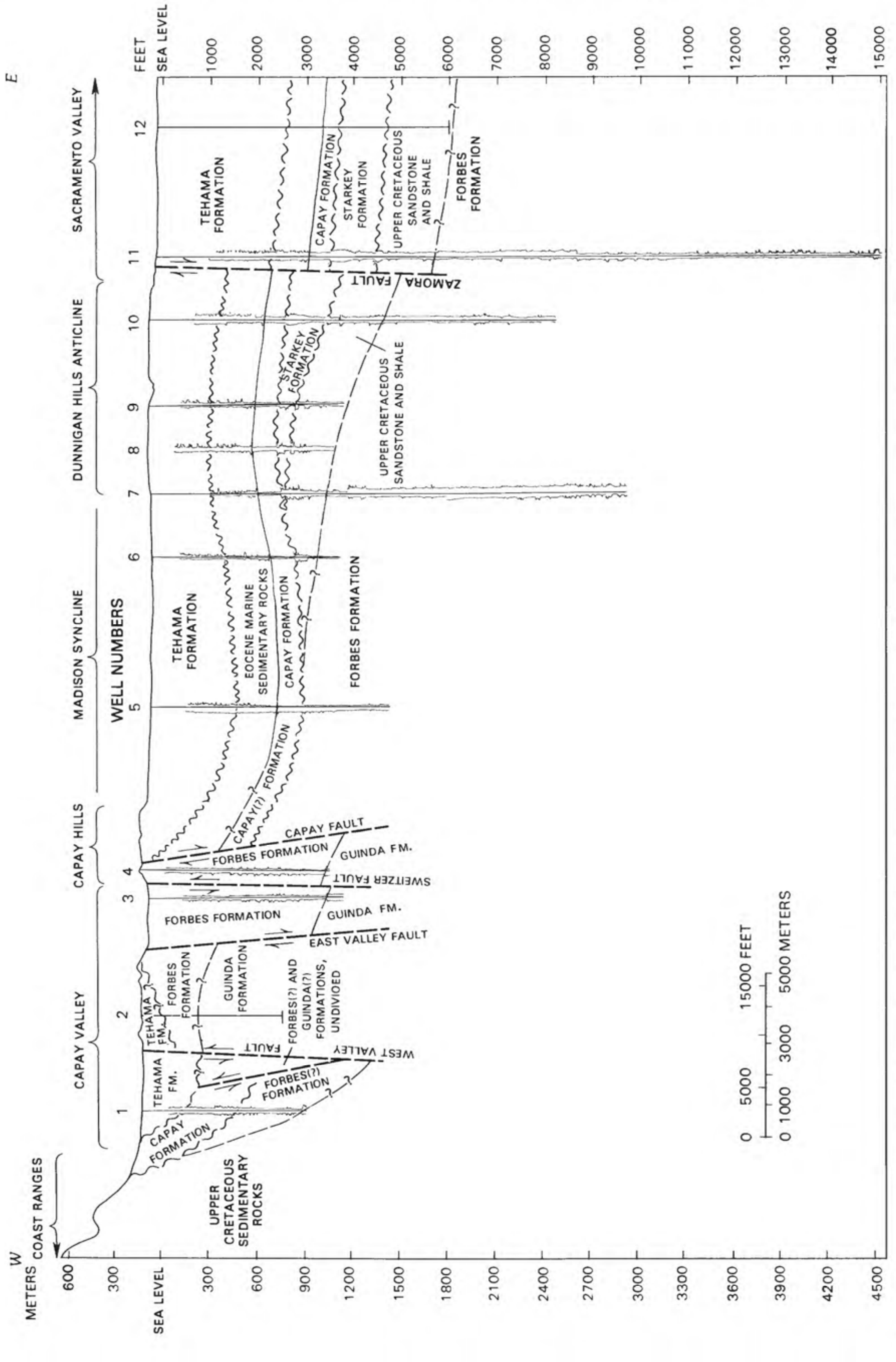


FIGURE 20.—Cross section showing electric logs and stratigraphic and structural relations in Capay Valley, Capay Hills, and Dunnigan Hills. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

150 m to the west by the near-vertical West Valley fault (fig. 20). At the south end of Capay Valley, Upper Cretaceous rocks are thrust over the Eocene Capay Formation along a thrust or high-angle reverse fault that is exposed to the south along the east flank of the Coast Ranges (pl. 1). The location of this thrust or high-angle reverse fault is unknown east of the West Valley fault.

East of Capay Hills, the Capay Formation unconformably overlies east-dipping Upper Cretaceous rocks beneath the Madison syncline and the Dunnigan Hills anticline (pl. 1; fig. 20). The Capay Formation and overlying Eocene marine rocks are not exposed in the Capay Hills where the Pliocene Tehama Formation rests unconformably on Upper Cretaceous rocks. Because the Capay Formation is present west of Capay Valley, however, we assume that the Capay Formation once extended over the area of the Capay Hills but that it was eroded from the area after west-side-up movement on the Capay fault (fig. 20) and the other high-angle reverse faults to the west under Capay Valley. In this interpretation, the minimum displacement on the Capay fault would be about 700 m. Major west-side-up reverse movement occurred on the Capay fault, the East Valley fault, and the unnamed thrust or high-angle reverse fault to the west in post-Eocene time and before deposition of the Tehama Formation, which contains the 3.4-m.y. old Putah Tuff Member near its base (Sarna-Wojcicki, 1976). West-side-down movement occurred on the West Valley fault subsequent to deposition of the Tehama Formation, and east-side-down, post-Tehama displacement also may have occurred on the East Valley fault and the Capay fault.

DUNNIGAN HILLS ANTICLINE AND THE ZAMORA FAULT

Near Woodland, Bryan (1923) recognized accordant summit elevations capped by Red Bluff gravel on a series of northwest-trending dissected uplands that he called the Hungry Hollow Hills, but which are now known as the Dunnigan Hills. The northeast flank of the upland is bounded by a linear escarpment that Bryan called the Hungry Hollow fault, but which is referred to here as the Zamora fault ([illegible]; fig. 20). He recognized down-to-the-[illegible] displacement of at least 121 m at the north end of the fault scarp and offset of about 60 m near Cache Creek to the south (Bryan, 1923, p. 79).

Bryan's early work, combined with the topographic relief in the area, made the Dunnigan Hills a prime target for early seismic-reflection studies that resulted in the discovery of the Dunnigan Hills gas field in 1946 (Rofe, 1962). The gas-producing structure is a doubly plunging, northwest-trending anticline along which various Upper Cretaceous sandstone beds are unconformably capped by the Eocene Capay Formation (fig. 20). This major structure has topographic relief. Red Bluff gravel wraps around the northwest-plunging nose of the fold and occurs in scattered patches along the east flank, on the crest line, and at the southeast-plunging nose of the fold. Oat Creek (pl. 1) and Bird Creek to the southeast (not shown on pl. 1) are antecedent to the fold and change from southeast to northeast courses approximately at its axial trace.

Data from a recent well drilled near Zamora by the U.S. Geological Survey provide new information on the amount of late Cenozoic deformation in the area. A conspicuous volcanic ash bed, penetrated at a depth of −137 m (Page and Bertoldi, 1983), has been correlated tentatively by mineralogy and chemical composition of the glass with the Rockland ash bed by C. E. Meyer and A. M. Sarna-Wojcicki (oral commun., 1982). Because the ash occurs directly above Red Bluff gravels elsewhere in the valley (Harwood and others, 1981; Helley and others, 1981), it is assumed that the ash overlies the Red Bluff in the Zamora well and that there is a minimum of 220 m of vertical displacement of the Red Bluff Formation. This vertical separation is the result of folding on the Dunnigan Hills anticline and displacement on the Zamora fault (fig. 20).

MIDLAND FAULT

The Midland fault is a major subsurface structure that was discovered in the Sacramento Delta during development of the Rio Vista gas field between 1936 and 1943 (Frame, 1944). Through data from extensive drilling, the fault was extended about 25 km north of the Rio Vista field to the Maine Prairie gas field (Arleth, 1968). North of that field, the location of the Midland fault is uncertain. Redwine (1972) proposed that the Sweitzer fault, mapped by Kirby (1943b) in the Capay Hills, was the northwest continuation of the Midland fault. Although Jennings (1977) showed the Midland-Sweitzer fault connection, suitably queried, on his geologic map of California, that interpretation is no longer considered correct (C. Jennings, oral commun., 1981). The location of the Midland fault south of the Rio Vista gas field is uncertain.

In the Rio Vista gas field, the Midland fault is actually a north-trending, steeply west-dipping to vertical fault zone that offsets Paleocene and Eocene rocks down to the west in a series of fault blocks as shown in figure 21. Early in the development of the Rio Vista gas field, it became apparent that movement on the Midland fault had controlled local patterns of Tertiary sedimentation. Frame (1944) noted that the Capay Formation was significantly thicker west of the Midland fault, and he suggested that maximum movement occurred on the fault during or at the close of Capay deposition. Although the Capay Formation shows the greatest amount of syntectonic thickening across the fault, all of the Paleocene and Eocene units show some differential thickening west of the fault (Burroughs and others, 1968). In his detailed analysis of depositional and tectonic cycles in the southern Sacramento Valley, Almgren (1978) demonstrated approximately 610 m of episodic movement on the fault between the early Paleocene and early Oligocene. There is no indication that early Oligocene or younger deposits are offset by the Midland fault; therefore, it appears that the Midland fault was an active structural feature on the early Tertiary continental margin but that it has not been active in the late Cenozoic.

By combining data presented by Burroughs and others (1968) and Almgren (1978), it is possible to calculate approximate displacement rates on the Midland fault during the early Tertiary. Calculation of the displacement rates, shown in figure 22, assumes that displacement occurred on a single fault strand during the time deduced for various units by Almgren (1978) and that initial offset began in the Paleocene. Between 60 and 53 m.y. ago the slip rate was 3.8 cm/1,000 yr. The rate increased to a maximum of 7.2 cm/1,000 yr between 53 and 50 m.y., and it decreased significantly to 0.75 cm/1,000 yr between 49 and 42 m.y.

THORNTON ANTICLINE

The Thornton anticline, or the Thornton arch of Silcox (1968), is an east- to southeast-trending, west-plunging fold that is transected in part by closely spaced northwest-trending faults that generally show west-side-down displacements of less than 20 m. The fold extends from the east-central part of the Sacramento Delta to the vicinity of Lodi and provides structural control for several gas fields along its trace. Silcox (1968) provides the most detailed information on the structural development of the

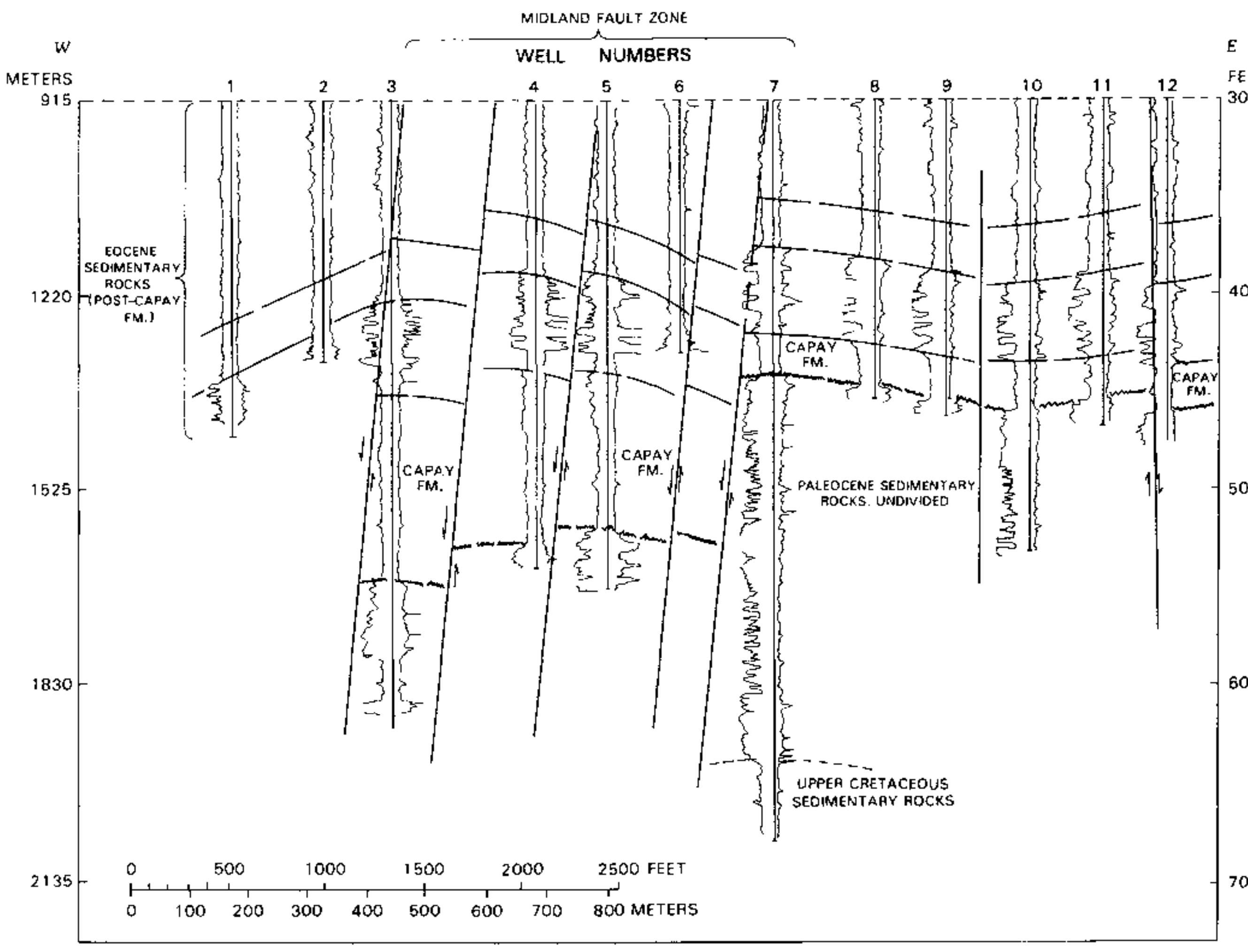


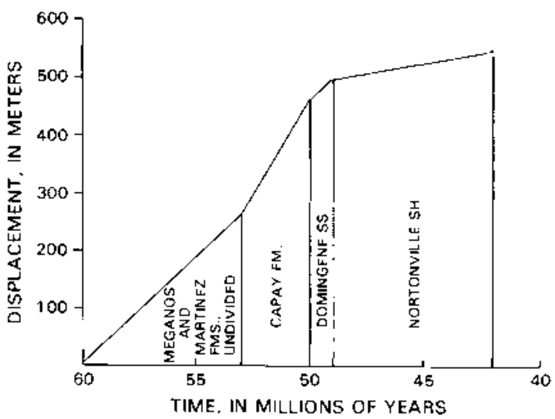
FIGURE 21.—Cross section showing electric logs and stratigraphic and structural relations across Midland fault zone in Rio Vista gas field (modified from Burroughs and others, 1968). Note significant thickening of the Eocene Capay Formation west of easternmost strand of Midland fault zone. Names of wells given by Burroughs and others (1968).

Thornton anticline in his description of the Thornton and Walnut Grove gas fields.

According to Silcox (1968) initial development of the Thornton anticline occurred prior to deposition of the basal Eocene rocks and may have been contemporaneous with Paleocene displacement on the Midland fault to the west. Maximum flexure of the structure apparently occurred in the late Eocene when lower and middle Eocene rocks were eroded and subsequently buried unconformably beneath deposits of the Markley submarine canyon. Miocene continental rocks, which were deposited unconformably on Markley canyon fill, do not show any significant folding over the Thornton anticline, nor are they offset by the northwest-trending faults that cut earlier deposits along the fold. Therefore, the structures are pre-Miocene.

STOCKTON FAULT

The Stockton fault is a northeast-trending, southeast-dipping subsurface fault that extends across the southern part of the Sacramento Valley between Tracy (south of pl. 1) on the west and the vicinity of Milton on the east. The fault lies north of a cross-valley, northeast-trending structural high in the basement, known as the Stockton arch, that apparently was discovered during some of the earliest seismic-reflection profiling done in the valley in the mid-1930's. Wells drilled near the Stockton fault during that time found only minor amounts of gas, and the



UNIT	DIFFERENTIAL THICKNESS (m)	POSTFORMATION OFFSET (m)	TOTAL OFFSET (m)	TIME (m.y. ago)	RATE (cm/10³ yr)
Nortonville Sh	15	38	53	(49-42)	0.75
Domingene Ss.	26	23	49	(50-49)	4.9
Capay Fm	215	0	215	(53-50)	7.2
Meganos and Martinez Fms., undivided	260	5	265	(60-53)	3.8

FIGURE 22.—Graph showing amounts and rates of offset on Midland fault zone, assuming all displacement occurred on a single fault strand and that displacement began in the Paleocene. Amount of offset and syntectonic thickening of units taken from figure 21 (modified from Burroughs and others, 1968).

relations between displacement on the Stockton fault and folding in the Upper Cretaceous marine rocks were not determined until development of the Lathrop gas field during the late 1940's. Teitsworth (1968), in his analysis of the Lathrop gas field, presents the most detailed study of the complex tectonic history of the Stockton fault. His work coupled with our analysis of wells to basement north of the Stockton fault, and Bartow's (1983) analysis of wells south of the fault provide the data for this discussion.

Near the city of Stockton, the −3,000-m basement contour is offset about 5 km in a left-lateral sense and depressed about 300 m down to the south, but the vertical component of movement is not closely controlled in that area. Eastward, near the −2,500-m contour, the basement surface is offset left-laterally about 6 km and depressed nearly 500 m south of the fault. The vertical component of displacement there is reasonably well controlled by wells north and south of the fault. Both the left-lateral and vertical components of displacement decrease eastward along the Stockton fault and appear to die out completely between the −500-m and 0 basement contours. No trace of the Stockton fault has been mapped in the exposed metamorphic rocks of the Sierran foothills between the north end of Gopher Ridge and the Mokelumne River (pl. 1) (Wagner and others, 1981).

Teitsworth's (1968) study of the Lathrop gas field (pl. 1, map A), which is located about 9 km southeast of Stockton, corroborates our analysis of the basement offset on the Stockton fault and adds valuable data about the amount and timing of deformation recorded in the Upper Cretaceous rocks. Teitsworth concluded that the Upper Cretaceous rocks were thicker south of the Stockton fault, indicating south-side-down vertical movement during early phases of deposition, and that they were subsequently offset about 3 km left-laterally during Late Cretaceous time. Deposition of Upper Cretaceous marine shale followed earlier strike-slip displacement on the Stockton fault, and these marine shale units also show left-lateral displacement. Following deposition and strike-slip displacement of the uppermost Upper Cretaceous unit in the area, but prior to deposition of Miocene continental strata that unconformably cap the Upper Cretaceous section, the Stockton fault experienced about 1,000 m of reverse, south-side-up movement (Teitsworth, 1968). During this period of reverse movement, west- and west-northwest-trending anticlines formed in the Upper Cretaceous rocks south of the fault, providing closure that trapped the gas in the Lathrop and East Stockton gas fields (pl. 1, map A). The trend of these folds and the northwest-trending anticlines in the Roberts Island and McDonald Island gas fields (pl. 1, map A) north of the Stockton fault indicate northeast-southwest compression in the area during the period of reverse movement on the Stockton fault. Teitsworth (1968) concluded that reverse movement probably occurred after the middle Eocene but before deposition of Miocene continental deposits. However, he shows a west-northwest-trending fold in contours drawn on the base of the Miocene rocks south of the Stockton fault, from which we conclude that the northeast-southwest compressive stress operated in the area into the middle Tertiary.

FAULTS IN THE SIERRAN FOOTHILLS

Clark (1960) combined data from a number of sources with his own field observations to produce the first regional structural synthesis of the Sierran foothills. He defined the Foothill fault system as a group of northwest-trending, steeply east-dipping to vertical faults that tectonically separate distinctive belts of Paleozoic and Mesozoic rocks for more than 320 km along strike in the western foothills of the Sierra Nevada. He recognized that the component faults in the system were actually complex fault zones marked by multiple fault strands and intensely sheared, cataclastic, and crumpled rocks, which were associated geographically, in many areas, with major bodies of sheared serpentinite. On the basis of limited paleontologic and radiometric data, he concluded that the major tectonic activity of the Foothill fault system occurred in the Late Jurassic.

Although displacement of Tertiary volcanic units was recognized locally along segments of the Foothill fault system after Clark's study (Bateman and Warhaftig, 1966), few investigations were made into the late Cenozoic deformational history of the fault system before the Oroville earthquake. That seismic event produced ground rupture on the Cleveland Hills faults (Clark and others, 1976) and opened the question of potential late Cenozoic deformation within the whole Foothill fault system.

In their earthquake evaluation studies of the Auburn Dam area, Woodward-Clyde Consultants (1977) made a regional analysis of potential late Cenozoic deformation along many linear features related to the Foothill fault system, and they trenched those linear features that had direct bearing on their Auburn Dam study. That study provided most of the data for our analysis of those strands of the fault system in the border zone between the Sierran foothills and the Sacramento Valley.

COHASSET RIDGE FAULT

Cohasset Ridge is a prominent south- to southwest-trending interfluve located northeast of Chico, between the major drainages of Big Chico Creek and Deer Creek. The ridge is capped by at least two essentially contemporaneous olivine basalt flows that appear to have originated in the Butte Mountain area (about 12 km east of pl. 1), on the southwest slope of a Pliocene volcano named Mount Yana by Lydon (1968). The olivine basalts flowed southwestward in channels eroded in the underlying Tuscan Formation, but subsequent erosion has inverted the topography so that the basalt now stands as the highest unit on the ridge. The olivine basalt of Cohasset Ridge represents the final phase of volcanism that reached the Sacramento Valley from Mount Yana. The upper basalt flow has been dated at 2.41 m.y. (Harwood and others, 1981).

East of Brushy Mountain (pl. 1), the olivine basalt of Cohasset Ridge is abruptly truncated on the east by a steeply east-dipping fault that strikes about N. 40° W., roughly parallel to the Chico monocline fault. Aune (cited in Woodward-Clyde Consultants, 1977) first recognized this fault, which he called the Cohasset Ridge fault, and concluded that the eastern equivalents of the olivine basalt of Cohasset Ridge were downfaulted to the east about 30 m along the normal fault. The Cohasset Ridge fault can be traced north of Deer Creek through an intensely fractured zone in the Tuscan Formation to the vicinity of Mill Creek, where it becomes obscured by a complex pattern of west- and northwest-trending arcuate faults (pl. 1; fig. 19). Although the area south of Deer Creek is heavily forested and the slopes are covered by a veneer of colluvium, the trace of the Cohasset Ridge fault is defined by a prominent topographic linear feature, observed by Rich and Steele (1974), that extends nearly to Magalia, where it apparently is intersected by the Magalia fault.

The Cohasset Ridge fault is a northwest-trending, steeply east-dipping fault that has experienced at least 30 m of east-side-down normal movement in the past 2.41 m.y.

MAGALIA FAULT

About 9 km north of Magalia, (pl. 1), the Cohasset Ridge fault is intersected by the N. 20° W.-trending Magalia fault. Extensive mine workings, which followed Tertiary auriferous gravel deposits at the base of the Tertiary volcanic sequence in the area, provide detailed data on the nature and local extent of the Magalia fault (Gassaway, 1899; Logan, 1930; Woodward-Clyde Consultants, 1977).

Although the Magalia fault is shown as a single fault on the map, detailed mine maps indicate that the fault is actually a complex fault zone consisting of numerous fault strands that have different orientations and amounts of displacement. In the Dix mine at the north end of the mining district, the gold-bearing gravels are offset 28 m down to the east. Southeastward along the trace of the Magalia fault at the Black Diamond mine, the gravel deposits are offset 68 m down to the east. Farther southeast at the Magalia mine, the channel deposits are offset down to the west from 2 to 11 m along three reverse faults that trend N. 60° W. and dip 58° NE.

From the mining records it appears that the various fault strands in the Magalia fault zone have experienced episodic and different movement through the Tertiary, with both normal east-side-down and reverse east-side-up displacement recorded. The relative ages of this disparate movement pattern along the Magalia fault are unknown, but the youngest movement appears to postdate movement on the Cohasset Ridge fault.

CLEVELAND HILLS FAULTS

The Cleveland Hills faults coincide with surface ruptures that occurred during the Oroville earthquake. During that seismic event, the ground surface failed in a 3.8-km long en echelon pattern of north- and north-northwest-trending normal faults that showed at least 55 mm of horizontal separation across the surface ruptures and as much as 180 mm of west-side-down vertical separation (Clark and others, 1976). Aftershocks of the Oroville earthquake defined a zone of seismic activity, assumed to coincide with the controlling fault, that dipped about 60° W. and trended nearly due north (fig. 15; also Bufe and others, 1976).

Trenches, dug across the zone of surface rupture by the California Department of Water Resources and logged by Akers and McQuilkin (1975), showed a gouge zone about 2 m wide in the bedrock below the surface ruptures that was flanked by 2-4 m of intensely fractured rock transitional into the country rock of foliated greenstone. The gouge zone contains anastomosing shear zones of deformed gouge that provide evidence of repeated earlier faulting along the zone of the ground failure. Earlier deformation in the area is also indicated by 30-60 m of apparent west-side-down offset of an erosion surface of probable Pleistocene age across the Cleveland Hills faults (Aune, 1975).

About 5.7 km northwest of the Cleveland Hills faults (pl. 1), Creely (1965) mapped a north-trending, steeply east-dipping fault that offset the base of Pleistocene or older gravel deposits about 2 m down to the west. Clark and others (1976) reported a second fault in the area that showed minor east-side-down offset of the gravel deposit.

FAULTS SOUTHEAST OF OROVILLE

In their earthquake evaluation of the Auburn Dam area, Woodward-Clyde Consultants (1977) identified a number of prominent linear features in the Sierran foothills southeast of the Cleveland Hills faults. With the exception of the northeast- and north-trending Highway 49 and Hancock Creek lineament zones (pl. 1), the linear features they investigated have northwest trends that coincide closely with the projected trace of the Chico monocline fault. The linear features were trenched extensively and logged in detail (Woodward-Clyde Consultants, 1977), and trench data were integrated with surficial geologic investigations in each area. Evidence of movement in the past 10 m.y. (Woodward-Clyde Consultants' definition of the "late Cenozoic") was detected in the trenches across the northwest-trending linear features, which are shown on plate 1 as the Swains Ravine, Spenceville, and Maidu fault zones and the Dewitt fault.

Deformation in the bedrock exposed in the trenches is remarkably similar to that shown in trenches across the Cleveland Hills faults. In most areas, bedrock beneath the surface lineaments contained one or more zones of slickensided clay-rich gouge a few meters wide or less. The gouge commonly contained anastomosing shear zones composed of polydeformed gouge and thin clay seams that indicated multiple phases of deformation. Rock adjacent to the gouge zones commonly was highly fractured, bleached, or manganese-stained and injected by thin quartz veins. In some trenches, a paleosol rested unconformably on bedrock and was offset locally along the faults marked by the gouge zones. That evidence led Woodward-Clyde Consultants (1977) to conclude that at least some of the faulting had occurred in the past 100,000 years. Based on the evidence presented by Woodward-Clyde Consultants (1977) and our observations in many of the trenches that they excavated during that study, we agree with their conclusions.

REGIONAL STRUCTURAL ANALYSIS

STRUCTURAL DOMAINS IN THE SACRAMENTO VALLEY

As we have shown in preceding sections of this report, late Cenozoic structural features in the valley have diverse orientations and displacement histories. In spite of this diversity, large areas of the valley are characterized by coeval structures that appear to have formed in a similar stress regime. To analyze the late Cenozoic structural evolution of the Sacramento Valley, we have grouped coeval structures that have similar displacement patterns into structural domains (fig. 23).

Delineating the various structural domains obviously depends on correctly identifying and correlating late Cenozoic deposits throughout the valley. Many of the late Cenozoic alluvial deposits are similar in outcrop characteristics, but fortunately they contain or are bracketed by distinctive tephra beds or volcanic flows that allow widespread correlation of alluvial units and provide absolute age control for the alluvial and tectonic histories of the region. In this regard, we have used the following time-stratigraphic units to define the late Cenozoic structural domains of the valley:

Unit	*Age/Age range (m.y.)*	*Reference*
Rockland ash bed	0.4-0.45	Sarna-Wojcicki and others (1985); Meyer and others (1980)
Red Bluff Formation	0.5-1.0	Harwood and others (1981)
Olivine basalt of Deer Creek	1.09	Harwood and others (1981)
Ishi Tuff Member of the Tuscan Formation	2.6	Harwood and others (1981; unpublished data, 1985)
Volcanic rocks of Sutter Buttes	1.4-2.4	Williams and Curtis (1977)
Nomlaki Tuff Member of the Tuscan and Tehama Formations	3.4	Evernden and others (1964)
Putah Tuff Member of the Tehama Formation	3.4	Sarna-Wojcicki (1976)

With the exception of the Dunnigan Hills, the structural domains shown in figure 23 become progressively younger northward through the valley. Late Cenozoic deformation in the Dunnigan Hills domain apparently overlapped that in the Corning domain, but the respective styles of deformation and the inferred stress regimes discussed in a later section differ significantly. This point emphasizes the fact that the structural domains include tectonic features that are homogeneous in time and style of deformation as far as we can determine. To a certain extent, the ages of the structural domains reflect the distribution of the time-stratigraphic units used to identify the major late Cenozoic deformation in a domain. It may be possible to subdivide some domains as more information on the distribution of the younger time-stratigraphic units becomes available. Furthermore, it is important to note that ascribing an age to the late Cenozoic deformation in a domain does not imply that all deformation necessarily began or ended within that time. Many late Cenozoic structural features in the valley formed over earlier structures in the upper Mesozoic or Tertiary rocks, and thus they owe their existence, in part, to tectonic heredity. In some areas, historic low-magnitude earthquakes can be identified with specific structural features such as the Battle Creek fault zone (Bolt, 1979) and Corning fault (Marks and Lindh, 1978), indicating that strain is currently being released on these structures.

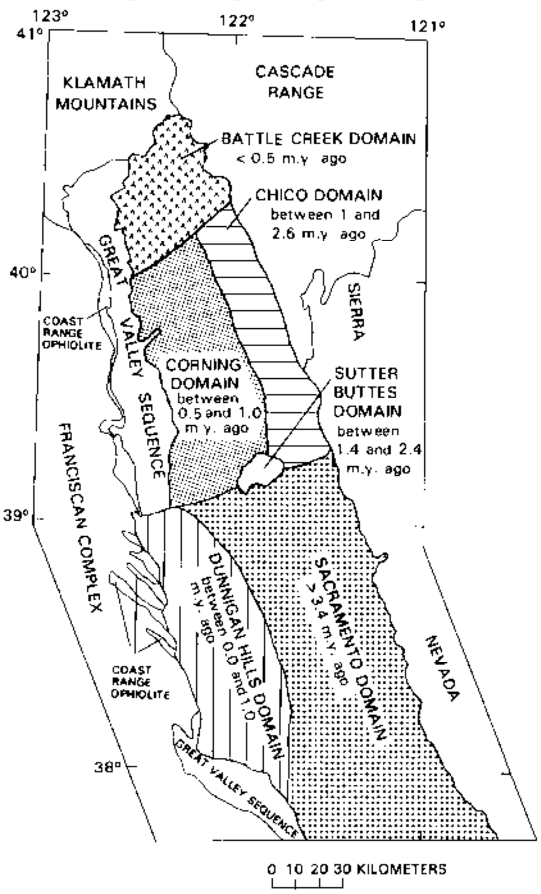


FIGURE 23.—Structural domains in Sacramento Valley. Numbers under domain names give duration or age of deformation that produced late Cenozoic structures in that domain.

SACRAMENTO DOMAIN

The Sacramento domain includes the Stockton fault, the Midland fault, the Thornton anticline, and the possible southeast extension of the Willows fault and other unnamed northwest-trending faults southeast of Sutter Buttes. None of these structures appear to offset or deform late Cenozoic alluvial deposits that are younger than the Nomlaki Tuff Member (figs. 7-10; Silcox, 1968; Teitsworth, 1968).

The minimum age of deformation is difficult to determine. If the Markley submarine canyon was localized, in part, by movement on the southeast extension of the Willows fault, as suggested by figures 8 and 9, then major deformation occurred in the domain in the middle Tertiary and could be as young as early Miocene, which is the upper age of the Markley canyon fill (Almgren, 1978). However, the Pliocene Laguna Formation, which contains the Nomlaki Tuff Member near its base just east of Marysville (Bussaca, 1982), does not appear to be offset in this domain; therefore, we conclude that deformation is older than 3.4 m.y. Upper Cretaceous rocks indicate syndepositional offset on the Stockton fault (Teitsworth, 1968) so the maximum age of deformation is Late Cretaceous.

The Willows fault north of Sutter Buttes (fig. 3) and the faults in Capay Valley (fig. 20) also show protracted deformation, ranging in age from Late Cretaceous to the middle Tertiary, that undoubtedly was contemporaneous with deformation in the Sacramento domain.

SUTTER BUTTES DOMAIN

The complex pattern of folds and faults at Sutter Buttes and the buried Colusa dome was interpreted by Williams

(1929) and Williams and Curtis (1977) to have formed by forceful intrusion of magma between 2.4 and 1.4 m.y. ago. Harwood (1984; this report) suggested that magmatism was localized at Sutter Buttes and the buried Colusa dome by movement on the Willows fault and possibly on the Mesozoic tectonic boundary between oceanic and Sierran basement terranes beneath Sutter Buttes. In this interpretation, deformation in the Sutter Buttes domain occurred through the combined effects of forceful intrusion of magma and east-west compression in a regional stress field.

Deformation in the Sutter Buttes domain may have overlapped in time with deformation in the Chico domain. However, the style of tectonism at Sutter Buttes is unique, and the area must be considered as a separate domain in a regional analysis.

Although Williams and Curtis (1977) suggested that Sutter Buttes formed in roughly half a million years, based on volume and morphology of volcanic deposits, their K/Ar ages for the volcanic complex range from about 1.4 to 2.4 m.y., and we have used that age range as the age of the structural domain.

CHICO DOMAIN

The Chico monocline is the dominant structure in the Chico domain (fig. 23). The monoclinal flexure and the controlling fault at depth (fig. 14) formed after the eruption of the Ishi Tuff Member of the Tuscan Formation, about 2.6 m.y. ago (Harwood, unpub. data, 1984), but before the eruption of the olivine basalt of Deer Creek, about 1.0 m.y. ago (Harwood and others, 1981). Formation of the monocline resulted directly from uplift of the northern Sierra Nevada and rupture along the controlling fault beneath the monocline. On the basis of geophysical evidence (Griscom, 1973; Cady, 1975), it seems reasonably certain that the controlling fault was a major late Mesozoic structure, separating oceanic from magmatic-arc crustal blocks, that was reactivated in the late Cenozoic.

Late Cenozoic tectonic uplift markedly increased erosion in streams antecedent to the monocline from Deer Creek northwest to Salt Creek just east of Red Bluff. Due to their tectonically steepened gradients, these streams deposited coarse, bouldery alluvial fanglomerate composed of volcanic material derived from the Tuscan Formation, extending from the monoclinal arch westward into the valley. The olivine basalt of Deer Creek filled the ancestral channel of Deer Creek east of the monocline and cascaded over the coarse fanglomerate, forming westward-overturned folds at the base of the flow west of the monoclinal flexure.

In Salt Creek and along nearby Hogback Road just east of Red Bluff, the fanglomerate (unit QTog of Harwood and others, 1981) rests unconformably on a partially stripped soil that developed on the Tuscan Formation. The soil indicates a significant period of nondeposition and weathering prior to flexing of the monocline and prior to rapid deposition of the alluvial fanglomerate. A period of erosion also followed deposition of the fanglomerate. The Red Bluff Formation was deposited unconformably on both the Tuscan and fanglomerate in Salt Creek. These stratigraphic relations, coupled with the fact that the Ishi Tuff Member is flexed, eroded, and unconformably overlain by the olivine basalt of Deer Creek along the monocline, establish deformation in the Chico domain between 1.0 and 2.6 m.y. This is clearly before deformation in the Corning domain to the west, where the Red Bluff is significantly folded and faulted.

The orientation of the horizontal compressive stress vector is not closely constrained in the Chico domain. Slickensides on some faults along the monocline flexure have a rake of 35° NW., suggesting some left-lateral oblique slip on the northwest-trending fault system. Whether the slickensides developed at the time the monocline formed or subsequently is unknown, but if they do record strain released during flexing of the monocline, the principal horizontal stress may have been oriented approximately east-west.

CORNING DOMAIN

West of the Chico monocline in an area extending to the Willows fault, late Cenozoic structures range in orientation from northwest to approximately north. The main stem of the Willows fault and the fault along the flank of South Corning dome nearly parallel the trend of the Chico monocline. On the other hand, the Corning fault, the Corning domes, and the Los Molinos and Glenn synclines trend more northerly than the monocline and converge on that structure near Red Bluff. All of these structures, within the Corning domain (fig. 23), deform the Red Bluff Formation and thus postdate the flexing of the Chico monocline. However, the subparallel orientation of structures in the Corning domain northeast of the Willows fault and of those in the Chico domain suggests that all may have formed in a common stress field.

The maximum horizontal compressive stress probably was oriented approximately east-west, normal to the trace of the Corning domes. The Corning fault might represent one shear diagonal of the strain ellipse, and the northwest-trending faults would indicate the other shear diagonal. In this model, strain release would have migrated westward with time, beginning along the Chico monocline and later moving to the Corning domes and Corning fault. Clearly, some offset may have occurred on the Corning fault and the northwest part of the Willows fault during formation of the monocline, and the small amount of offset in the olivine basalt of Deer Creek over the monocline may have occurred during the upwarping of the Red Bluff

Formation over the Corning domes.

The area of the Corning domain southwest of Sutter Buttes and the Willows fault is largely capped by Holocene basin deposits that lap westward onto Upper Cretaceous rocks along the western margin of the valley. These deposits could obscure many structures that might be recorded in the Red Bluff Formation in that area, indicating that the downthrown side of the Willows fault has been a structural basin throughout most of the late Quaternary.

DUNNIGAN HILLS DOMAIN

The Dunnigan Hills domain (fig. 23) includes the Zamora fault, the Dunnigan Hills anticline, the Madison syncline, and the tectonically complex area of Capay Valley and the Capay Hills. The Red Bluff Formation is folded by the Dunnigan Hills anticline and offset by the Zamora fault along the east margin of the Dunnigan Hills (fig. 20). Therefore, the late Cenozoic structures in that area are at least as young as the folds and faults in the vicinity of Corning domes, and they could be younger. Because there is no clear evidence for the minimum age of structures in the domain, we assume that late Cenozoic deformation ranges from 1.0 m.y. to the present.

Although the late Cenozoic deformation may overlap in time with that in the Corning and Battle Creek domains, the orientation and movement pattern of structures are significantly different. The northwest-trending axial surface of the Dunnigan Hills anticline and normal displacement on the northwest-trending Zamora fault suggest that these structures may have formed in a stress field in which the maximum horizontal compressive stress was oriented approximately north-south and the least horizontal compressive stress (maximum extension) was oriented approximately east-west. Because this is the present orientation of the stress field associated with the San Andreas fault in this area (Zoback and Zoback, 1980), late Cenozoic structures in the Dunnigan Hills domain may be related to right-slip wrench tectonism associated with movement on the San Andreas fault system (Allen, 1981).

BATTLE CREEK DOMAIN

The Battle Creek domain (fig. 23) is the youngest structural domain and occurs at the northern end of the valley. It is characterized by northeast-trending folds and faults oriented nearly perpendicular to the north- and northwest-trending structures of other domains to the south.

Late Cenozoic displacement on the northeast-trending, steeply south-dipping faults is invariably down to the south, with a suggestion of minor right-lateral slip on the Battle Creek fault system (Helley and others, 1981). The amount of horizontal separation on the Battle Creek fault is unknown, but it probably is on the order of a few tens of meters to a few hundred meters at the most. The Bear Creek and Red Bluff faults are not exposed well enough to establish or refute the occurrence of late Cenozoic horizontal slip on those structures. The amount of vertical displacement increases eastward along the Battle Creek fault zone, with about half of the vertical separation of units caused by broad anticlinal folding and half by fault displacement (fig. 17). Vertical separation of late Cenozoic units on the Bear Creek and Red Bluff faults is also accomplished partly by folding.

These observations, plus the fact that the Inks Creek fold system appears to be genetically related to folding and faulting on the Battle Creek fault zone, indicate that the structures in the Battle Creek domain formed either by northwest-southeast horizontal compressive stress or by right-lateral shear stress. Strain was released initially by folding, followed by rupture and predominantly normal fault displacement. Initial movement on the Battle Creek fault zone postdated deposition of fanglomerate, which is correlated with the Red Bluff Formation, and the fault scarp restricted movement of the proximal ash-flow part of the Rockland ash bed. Deformation younger than 0.45 m.y. is indicated by distribution of the early Riverbank-age alluvial deposits north of the Battle Creek fault zone and in the tectonically controlled loops of the Sacramento River around the Inks Creek fold system. The late Cenozoic structures in the Battle Creek domain formed in the past half million years.

Little surface evidence is available to document deformation before the late Cenozoic in the Battle Creek domain. A detailed analysis of paleomagnetic directions and lithofacies in the Upper Cretaceous marine rocks and Eocene continental rocks, which locally overlie the Cretaceous rocks, might provide data to resolve this question, but we did not pursue these studies. In the light of recent paleomagnetic studies (Simpson and Cox, 1980; Beck and Plumley, 1980; Magill and Cox, 1981), which suggest a two-phase, clockwise rotation of the Oregon Coast Ranges and possibly of the Klamath Mountains in Eocene and post-Oligocene times, we believe the Battle Creek domain may be a zone of decoupling between the Klamath Mountains and Oregon Coast Ranges provinces to the north and the Sacramento Valley-Sierra Nevada provinces to the south.

VALLEY STRUCTURES RELATED TO REGIONAL STRESS PATTERNS

With the exception of structures in the Dunnigan Hills domain and recent movement on the Cleveland Hills faults, late Cenozoic folds and faults in the Sacramento Valley appear to have formed in an east-west compressive stress regime. The north- and northwest-trending

Willows, Corning, and Chico monocline faults dip steeply east and show reverse displacements. The east-northeast-trending Red Bluff, Battle Creek, and Bear Creek faults dip steeply south and have normal offsets. The axial traces of many folds are parallel to the trends of adjacent faults, and the folding appears to be related to drag on those faults. The amount of lateral displacement on faults in the valley is difficult to determine, but the rake of slickensides and the orientation of ancilliary fractures suggest minor left-lateral movement on the northwest-trending Chico monocline fault and minor right-lateral slip on the east-northeast-trending Battle Creek fault zone. These kinematic patterns are consistent with a regional stress field in which the maximum horizontal component of compressive stress is oriented about N. 75° E. (Harwood, 1984).

The late Cenozoic kinematic pattern and inferred east-west compressive stress regime in the Sacramento Valley appear to be anomalous with respect to contemporary tectonism in adjacent regions. In the California Coast Ranges to the west and in the northern Basin and Range province to the east, north-trending faults generally show normal and right-lateral displacements, east-trending faults show reverse and left-lateral movement, and northwest- and northeast-trending faults show dominantly right-lateral and left-lateral displacement, respectively (Zoback and Zoback, 1980; Hill, 1982). From these kinematic patterns, as well as earthquake focal-plane solutions, and in-situ stress measurements, Zoback and Zoback (1980) and Hill (1982) inferred that the maximum horizontal compressive stress was oriented approximately north-south and the least horizontal compressive stress (maximum extension) was oriented approximately east-west. Hill (1982) related the contemporary stress patterns to movement between the North American and Pacific plates and visualized the western part of the North American plate as a continuous broad zone of deformation following the model first proposed by Atwater (1970).

East-west compressive deformation in the Sacramento Valley suggests that the late Cenozoic stress field was not homogeneous between the continental margin and the northern Basin and Range province. Instead, the Sacramento Valley apparently acted as an independent block where relatively small-scale compressive strain was periodically released in response to large-scale right-lateral transform tectonism in the San Andreas fault zone to the west and major east-west crustal extension in the northern Basin and Range province to the east.

Furthermore, the well-dated deformation patterns in the Sacramento Valley indicate that the compressive strain was not released randomly but, rather, that the late Cenozoic structural features formed in a sequential pattern that is progressively younger to the north. Northward progression of the compressive deformation implies a northward-migrating stress regime or a migrating energy source sufficient to initiate deformation in a regional compressive stress field. The interaction of lithospheric plates along the continental margin appears to provide a reasonable mechanism for generating the sequential compressive strain release observed in the valley.

Successive positions of the Mendocino transform, extrapolated backward in time to 4.0 m.y. at a rate of 5.5 cm/yr (Atwater and Molnar, 1973), are shown relative to the late Cenozoic structural domains in the Sacramento Valley in figure 24. Each domain is characterized by a particular set of late Cenozoic structural features that formed during a definite period of time. The time of deformation in the structural domains is linked to respective positions of the Mendocino transform by corresponding patterns on figure 24. Compressive deformation in the Sacramento domain occurred prior to eruption of the Nomlaki and Putah Tuff Members of the Tehama Formation about 3.4 m.y. ago, but we are unable to correlate movement on specific structures in that domain with relative plate motions shown by successive positions of the Mendocino transform. Beginning with magmatism and deformation in the Sutter Buttes domain about 2.4 m.y. ago, however, reasonable correlation exists between the position of the Mendocino transform and progressive east-west compressive deformation in the Sacramento Valley. This correlation clearly reflects the availability of geologic information that dates deformation in the northern part of the valley, but it may also reflect a greater degree of tectonism in the valley over the past 2.4 m.y. that was related to increased tectonism ahead of the advancing Mendocino triple junction (fig. 24).

According to Silver (1971), an episode of major bending and fracturing occurred in the Juan de Fuca plate (fig. 24) between 2.5 and 0.5 m.y. ago. This deformation apparently increased the north-south compressive stress ahead of the advancing Mendocino triple junction and caused underthrusting of oceanic crust in the Juan de Fuca plate beneath the Mendocino transform. Dickinson and Snyder (1979a) suggested that this type of instability at the Mendocino triple junction would increase the east-west extensional stress in the vicinity of the triple junction and possibly cause eastward migration of right-slip strain release along the San Andreas fault zone. Internal deformation of the Juan de Fuca plate also may have changed the rate and relative motion of the subducted part of that plate relative to the North American plate sufficiently to initiate magmatism at Sutter Buttes and at the Pliocene volcanic centers of Mount Yana and Mount Maidu (fig. 24) (Lydon, 1968) about 2.4 m.y. ago. Subsequent relative movement of the North American plate southwestward from its position above the subducted Juan de Fuca slab, over the eastern projection of the Mendocino transform and onto the area of the slab window of Dickinson and Snyder (1979b), may have initiated progressive deformation in the Sacramento Valley north of the Sutter Buttes domain.

According to Dickinson and Snyder (1979b), an expanding, triangular-shaped region, which they called the slab window, has developed east of the lengthening San Andreas transform since the rise-trench encounter about 20 m.y. ago. As the slab window expanded, upwelling asthenosphere came into contact with the base of the North American crust producing an expanding region of Neogene extensional tectonism. The northern boundary of the slab window, which is the eastern projection of the Mendocino transform, migrated northward as a consequence of the northward migration of the Mendocino triple junction and relative motion between the North American and Juan de Fuca plates. Successive positions of the northern boundary of the slab window beneath the Sacramento Valley for the past 2.5 m.y. are shown in figure 25.

About 2.5 m.y. ago, the northern boundary of the slab window was located approximately at the latitude of Sutter Buttes (fig. 25*A*). As the North American plate moved southwestward relative to the Juan de Fuca plate, the base of the valley crust near Sutter Buttes moved off the subducted ocean crust of the Juan de Fuca plate and encountered asthenophere in the slab window. This change in thermal regimes at the base of the valley crust possibly reactivated the Willows fault and the ancient tectonic boundary between ophiolitic basement rocks and the Sierran basement rocks, allowing magma to rise and differentiate below Sutter Buttes and the buried Colusa dome. Subsequent southwestward relative movement of the North American plate exposed an increasing area of the Sacramento Valley and northern Sierra Nevada crustal blocks to the higher thermal regime of the slab window. Basaltic volcanism erupted in the Tahoe-Almanor graben (fig. 25*A*) north of Lake Tahoe soon after magmatism began at Sutter Buttes (Dalrymple, 1964). Ac-

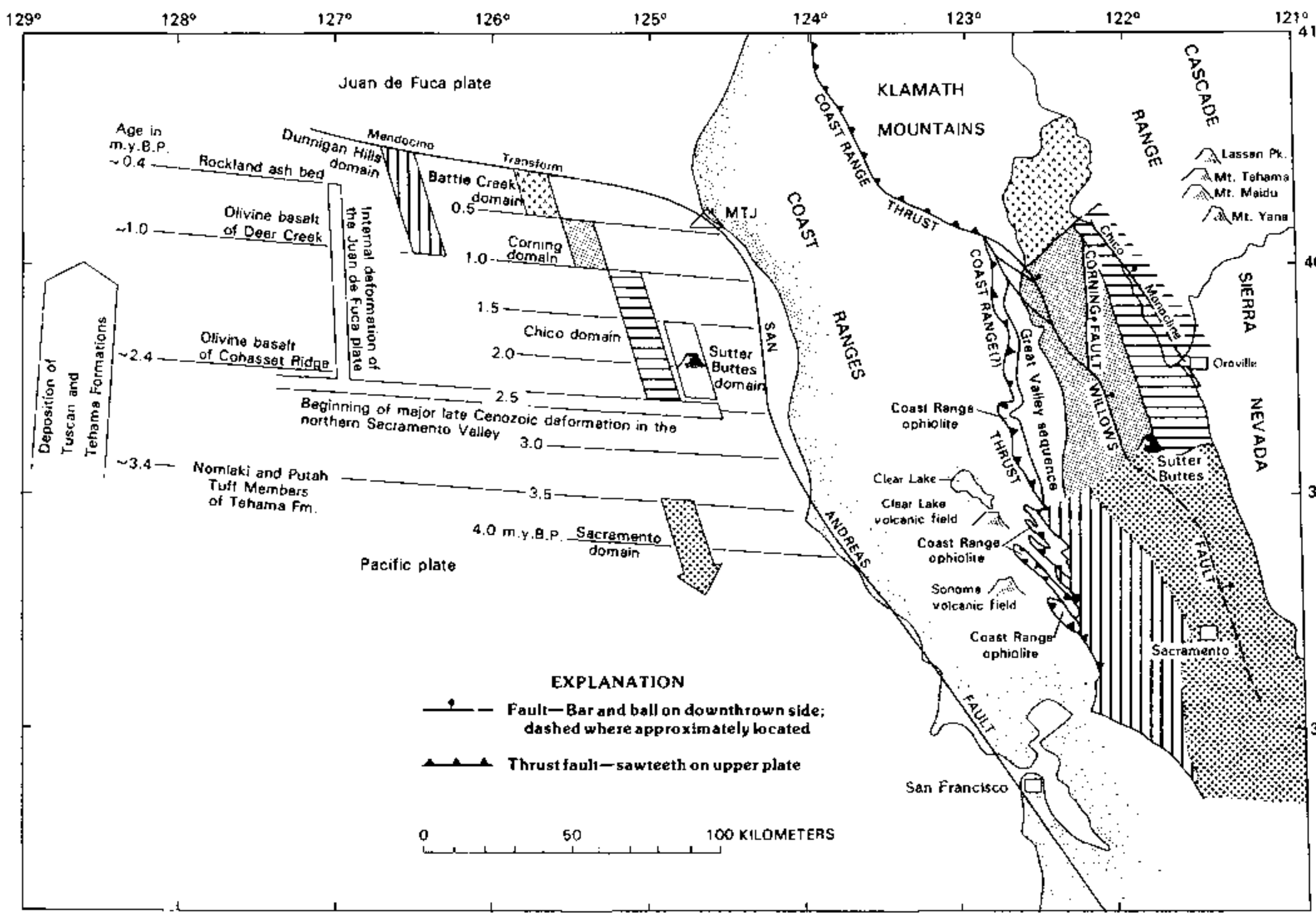
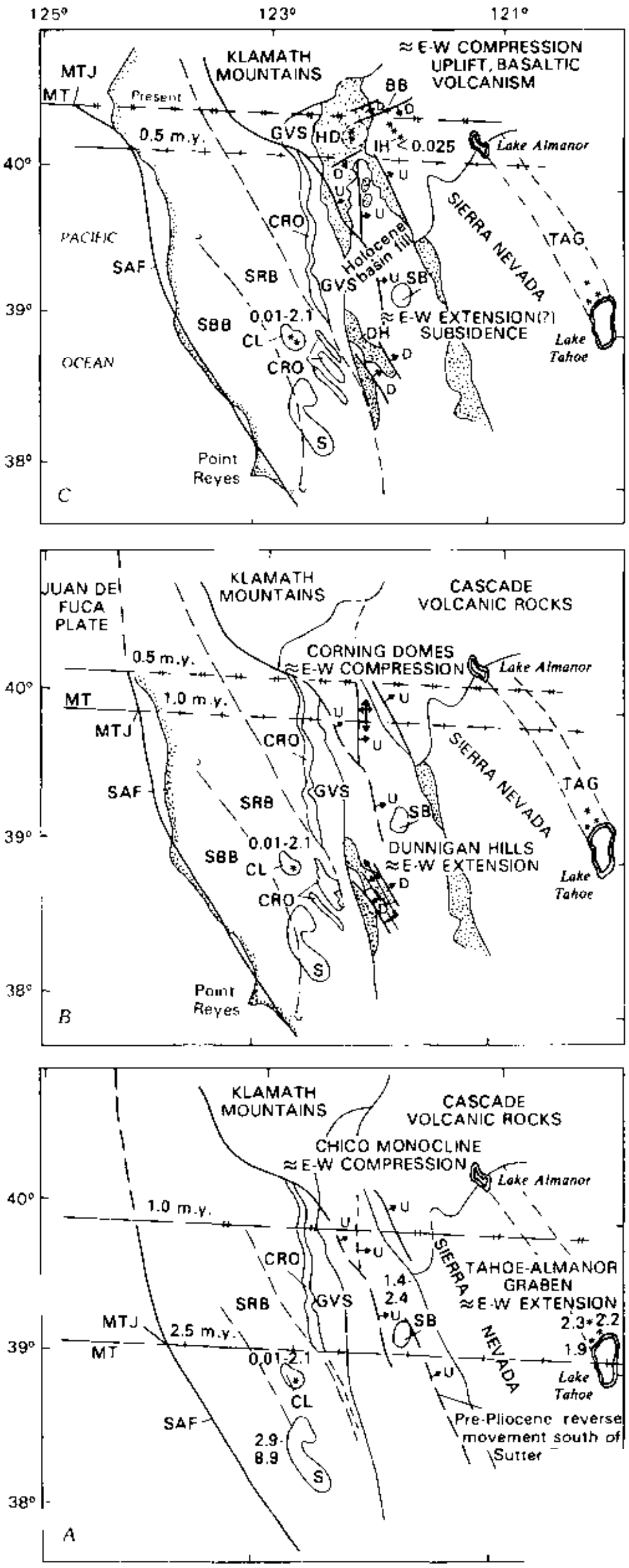


FIGURE 24.—Map of northwestern California relating late Cenozoic structural features and structural domains (patterned) to inferred position of the Mendocino triple junction (MTJ) during time structures formed. Position of Mendocino transform shown in 0.5-m.y. increments during past 4.0 m.y. Dated volcanic units used to bracket age of deformation in Sacramento Valley shown at left.

celerated uplift of the Sierra Nevada, which began about 3.0 m.y. ago in the central part of the range (Huber, 1981; Slemmons and others, 1979), eventually caused rupture between 2.5 and 1.0 m.y. ago along the Mesozoic fault that separates valley and Sierran blocks beneath the Chico monocline. Volcanism at Clear Lake (fig. 25), which began about 2.1 m.y. ago (Donnelly-Nolan and others, 1981), lagged behind passage of the northern boundary of the slab window and has continued nearly to the present.

Between 1.0 and 0.5 m.y. ago (fig. 25*B*), exposure of the base of the valley crust to the slab window may have reactivated the basement fault in the vicinity of the Corning domes, resulting in east-west compressional tectonism. Wrench tectonism and related east-west extension apparently started to affect the southwestern part of the valley after creating a zone of high shear strain in the Santa Rosa block (Fox, 1983), located in the eastern part of the Coast Ranges province. This is the earliest evidence of east-west extensional tectonism found in the valley and suggests a delay time of about 2.5 m.y. between passage of the slab-window boundary and production of recognizable extensional structures.

In the past 0.5 m.y., the northern boundary of the slab window has passed beneath about half of the Battle Creek domain (figs. 24, 25*C*). The morphology of the valley in the Battle Creek domain, therefore, may reflect recent,



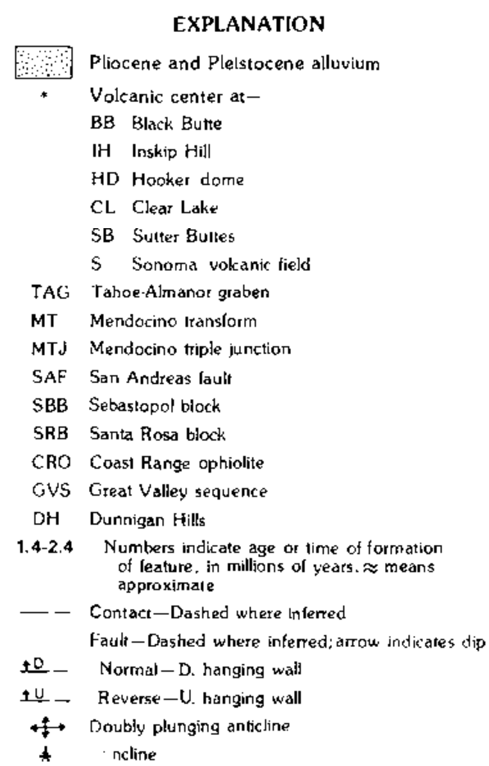


FIGURE 25.—Sketch maps of northwestern California showing inferred positions of northern boundary (barbed dashed lines) of slab window of Dickinson and Snyder (1979b) at about 2.5 and 1.0 m.y. (*A*), 1.0 and 0.5 m.y. (*B*) and 0.5 m.y. and present (*C*).

and possibly on-going, structural changes in the deeper parts of the valley fill and basement caused in part by changes in the thermal regime beneath the thick valley crust. This hypothesis was investigated by Helley and Jaworowski (1983), who used the distribution of the Red Bluff pediment as a surface indicator of deeper valley structures. The elevation of the floor rises abruptly north of Red Bluff, and the dissected uplands expose the Pliocene Tehama Formation that is unconformably capped by remnants of the Red Bluff Formation. Drainage patterns reflect local structures, such as Hooker dome (fig. 18), and major creeks locally follow the dominant northeast structural trends. The gradient of the Sacramento River steepens significantly across the Battle Creek domain, and its incised meanders are structurally controlled. Many of these geomorphic features are preserved, in somewhat more subdued form, around Corning domes and elsewhere in the valley south of Red Bluff (Helley and Jaworowski, 1985).

The northeast-trending Inks Creek fold system and the folding associated with the Battle Creek and Red Bluff faults suggest a northwest-southeast compressive stress system. If such is the case, however, normal displacement on the Bear Creek, Battle Creek, and Red Bluff faults are anomalous. The structural features in the Battle Creek domain may reflect a stress regime in which the maximum horizontal compressive stress (east-west) and the least horizontal compressive stress (north-south) vectors are more nearly equal. This inferred change in the stress pattern may be caused by oblique subduction of the Juan de Fuca plate and the possible buttressing effect of the Klamath Mountains on deformation in the northernmost part of the Sacramento Valley.

CONCLUSIONS

Kinematic patterns of late Cenozoic structural features in the Sacramento Valley differ significantly from those in the Coast Ranges province to the west and the northern Basin and Range province to the east. Certainly for the past 2.5 m.y., and probably much longer, deformation in the valley has occurred in a regional stress field in which the maximum horizontal component of compressive stress was oriented approximately east-west and the minimum component of compressive stress (maximum extension) was oriented approximately north-south. Within this stress regime, strain has been released primarily by reverse movement on north- and northwest-trending high-angle faults and associated folding in the sedimentary rocks of the valley fill. This style of deformation contrasts sharply with the pattern of northwest-trending en echelon folds and pull-apart basins, and east-west oriented thrust faults associated with large-scale right-lateral displacements on the San Andreas fault system (Blake and others, 1978; Graham, 1978; Harding, 1976; McLaughlin, 1981; Page, 1981) and the pattern of pervasive normal faulting, widespread volcanism, and large-scale east-west extension in the Basin and Range province (Christiansen and Lipman, 1972; Lipman and others, 1972; Zoback and others, 1981). During the late Cenozoic, the Sacramento Valley appears to have acted as an independent block on which relatively small-scale compressive deformation was imposed by eastward-directed subduction that was followed by large-scale transform tectonism along the continental margin and major east-west crustal extension in the Basin and Range. Early Tertiary deformation on the Willows fault and in the area of Capay Valley may be related to eastward tectonic wedging of the Franciscan Complex described by Wentworth and others (1984).

Tectonic heredity appears to have played a significant role in late Cenozoic deformation in the Sacramento Valley. Many of the faults that break or drape the upper Cenozoic deposits are located over pre-existing structures within and at the boundaries of basement blocks that were tectonically juxtaposed and broken during the Mesozoic and early Tertiary. The tectonic boundary between ophiolitic and Sierran basement rocks apparently has been reactivated beneath the Chico monocline and the possible southeast extension of the Willows fault. The Corning fault occurs over a Mesozoic fault within the ophiolitic basement terrane.

Within the past 2.5 m.y., at least, late Cenozoic east-west compressive deformation has progressed northward so that structures observed in the Battle Creek domain are a million years younger than those around Sutter Buttes. The northward progress of late Cenozoic deformation correlates with extrapolated positions of the Mendocino transform. Deformation may have been initiated by thermal changes in the valley basement as the North American plate moved relatively southwestward off the subducted oceanic crust of the Juan de Fuca plate and over asthenosphere in the slab window proposed by Dickinson and Snyder (1979b). During this sequential deformation, the relative magnitude of the horizontal compressive stress vectors appears to have changed. The kinematic pattern of structures south of Red Bluff suggests that east-west compression was dominant ($S_{maxEW} >> S_{minNS}$) and resulted in high-angle reverse faulting. However, the horizontal compressive stresses appear to have been more nearly equal ($S_{maxEW} \cong S_{minNS}$) in the Battle Creek domain causing northeast-trending folds and normal displacements on east-northeast-trending faults.

Northwest-trending folds and normal displacement on the Zamora fault suggest that east-west extension may have affected the southwestern part of the valley during the past million years, when east-west compressive deformation was occurring in the Corning domain. Focal-plane solutions constrained by geologic data in the Clear

Lake area indicate that the maximum compressive stress in the Coast Ranges is presently oriented approximately north-south (Bufe and others, 1981). These data, coupled with the observation that right-lateral tectonism is more intense in the Coast Ranges adjacent to the Dunnigan Hills domain than it is to the west or north (Fox, 1983), suggest that late Cenozoic deformation in the Dunnigan Hills domain was related to wrench tectonism on the San Andreas fault system. If such is the case, the beginning of right-lateral wrench tectonism in the valley appears to have lagged behind the northward migration of the Mendocino triple junction by about 2.5 m.y. A similar delay was noted between the migration of the triple junction and the build-up of maximum heat flow in the Coast Ranges by Lachenbruch and Sass (1980).

The well-dated and diverse deformation patterns in the Sacramento Valley indicate that late Cenozoic tectonism evolved through the region in response to major crustal movements outside the valley's physiographic boundaries. East-west compressive tectonism may have been imposed on the valley by eastward subduction of the Juan de Fuca plate, and consequent tectonic wedging of the Franciscan Complex coupled with a major component of westward stress due to east-west extension in the Basin and Range province.

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APPENDIX—*Wells with electric well-log data shown in cross sections*

Well no.	Operator	Well name	Sec.-T.-R.
		Wells on figure 3	
1.	Texaco	Cross No. 1	27-20N.-3W.
2.	Franco Western Oil Co.	Dunlap 36-1	36-20N.-3W.
3.	Marathon Oil Co.	Capital Co. No. 1	30-20N.-2W.
4.	R. W. McBurney	Westpet Sunray McBurney Capitol No. 1	30-20N.-2W.
5.	Mobil Oil Corp.	Capital Co. No. 30-1	30-20N.-2W.
6.	Mobil Oil Corp.	Section 29 Unit No. 4	29-20N.-2W.
7.	R. W. McBurney	Section 29 Unit No. 2	29-20N.-2W.
8.	Mobil Oil Corp.	Section 48 Unit No. 4	21-20N.-2W.
9.	Mobil Oil Corp.	Section 48 Unit No. 1	21-20N.-2W.
10.	Standard Oil Co.	Doheny N. G. Unit No. 1	22-20N.-2W.
11.	Mobil Oil Corp.	Section 46 Unit No. 2	27-20N.-2W.
12.	Bettie A. McBurney	Reserve McBurney Unit S1 No. 1	26-20N.-2W.
13.	Bettie A. McBurney	Section 52 Unit No. 3	25-20N.-2W.
14.	Neaves Pet. Devel. Co.	Neaves Capital 53-1	32-20N.-1W.
15.	Mobil Oil Corp.	Dano Seco No. 1	33-20N.-1W.
16.	Calif. Time Pet. Inc.	Butte Dano Seco No. 4	34-20N.-1W.
		Wells on figure 7	
1.	Occidental	Zumwalt K-2	12-13N.-1E.
2.	Shell	Strat. test well	31-14N.-2E.
3.	G. E. Kadane & Sons	Lamb No. 1	30-14N.-2E.
4.	Atlantic	AMKH et al	28-14N.-2E.
5.	Atlantic	Continental Stent No. 1	15-14N.-2E.
6.	Kenneth L. Sperry	Shannon No. 1	10-14N.-2E.
7.	Exxon	Shannon No. 1	14-14N.-2E.
8.	Pearson Sibert	Tom No. 1	5-14N.-3E.
		Wells on figure 8	
1.	Sun Oil Co.	SMC Cameron Dougherty No. 1	31-12N.-3E.
2.	McCulloch Oil & Gas Corp.	McCulloch-Magoon et al. No. 1	32-12N.-3E.
3.	Davis Oil Co.	Aileen Marty No. 1	35-12N.-3E.
4.	Davis Oil Co.	Van Dyke No. 1	35-12N.-3E.
5.	Decalta Int. Corp.	Osterli No. 3	31-12N.-4E.
6.	Sun Oil Co.	Lenert No. 55-29	29-12N.-4E.
7.	Kenneth L. Sperry	Davis No. 1	21-12N.-4E.
8.	Plateau Oil & Gas Co.	Van Dyke No. 1	24-12N.-4E.
9.	Exxon	Bonnefeld No. 1	10-12N.-5E.
		Wells on figure 9	
1.	Rocky Mtn. Drilling Co.	Murdoch No. 1	27-7N.-4E.
2.	McCulloch Oil & Gas Corp.	Scribner No. 1	27-7N.-4E.
3.	Chevron	Correa No. 1	24-7N.-4E
4.	Neaves Pet. Devel. Co.	Neaves-Standard Oil Sims No. 3	18-7N.-5E.
5.	Chevron	Sims Comm. No. 2	18-7N.-5E.
6.	Calif. Expln. Co.	Sacramento Unit A	16-7N.-5E.
7.	Union Oil Co. of Calif.	Union Dow Attorney General No. 1	13-7N.-5E.
8.	Intex Oil Co.	Unit plan No. 1	19-7N.-6E.
9.	D. D. Feldman	Unit plan No. 1	8-7N.-6E.
10.	Norris Oil Co.	Waegell No. 1	6-7N.-7E.
		Wells on figure 10	
1.	Shell Oil Co.	Shell-Brevelli No. 1	4-4N.-6E.
2.	Amerada Hess Corp.	Comm. 1-2	2-4N.-6E.
3.	Amerada Hess Corp.	Comm. 1-1	1-4N.-6E.
4.	Aminoil USA, Inc.	Comm. 2-1	12-4N.-6E.
5.	Union Oil Co. of Calif.	V-B-G No. 1	7-4N.-7E.
6.	Amerada Hess Corp.	Lodi Comm. 8-1	8-4N.-7E.
7.	Amerada Hess Corp.	Lodi Comm. 9-1	9-4N.-7E.
8.	Shell Oil Co.	Ferrera No. 1-10	10-4N.-7E.
9.	Ben Owens Drilling Co.	Thompson No. 1	11-4N.-7E.
		Wells on figure 14	
1.	Solar Drilling Co.	Solar-McElroy-Crawford No. 1	5-23N.-1W.
2.	Pacific Western	Cana No. 1	11-23N.-1W.
3.	Exxon	C. U. Roney No. 1	1-23N.-1W.
4.	Exxon	C. C. Baccala No. 1	28-24N.-1E.
		Wells on figure 20	
1.	Neaves Pet. Devel. Co.	Neaves-Cobb No. 1	11-10N.-3W.
2.	Empire Oil and Gas Co.	Porterfield No. 1	18-10N.-2W.
3.	Texaco, Inc.	Esparto c.h. No. 2	17-10N.-2W.
4.	Dow Chemical Co.	Duncan No. 1	9-10N.-2W.
5.	Gulf Oil Corp.	A. B. Stevens No. 1	7-10N.-1W.
6.	Atlantic Oil Co.	Irrigated Valley Land No. 1	4-10N.-1W.
7.	A. A. Hopkins, Jr.	Manler No. 62-3	3-10N.-1W.
8.	C. K. M. Oil Co.	Mast No. 1	35-11N.-1W.
9.	Gulf Oil Corp.	L. M. Bemmerley No. 1	36-11N.-1W.
10.	E. B. Towne	Slaven No. 1	30-11N.-1W.
11.	Arco	Reiff No. 1	29-11N.-1W.
12.	Arco	Hermle No. 1	15-11N.-1E.

GPO 785-048/77389

Corin Choppin

From: B&S Wiggin <bwsw@frontier.com>
Sent: Thursday, December 17, 2020 11:05 AM
To: Mary Fahey
Subject: RE: Groundwater list

Mary,
One of our concern is on Sand Creek. 50 years ago that Creek spread out very wide & we believe that gave us recharge for our underground water. The county allowed gravel removal & the bank is now about 10 feet lower than it used to be, making the channel very narrow & the water runs very fast. We can't do anything about it because of Fish & game. They will allow some low berms as long as one side has no berm. This isn't much help.
Sharon Wiggin

From: Mary Fahey <mfahey@countyofcolusa.com>
Sent: Thursday, December 17, 2020 7:27 AM
To: Sharon Brett Wiggin <bwsw@frontier.com>
Subject: Groundwater list

Hi Sharon
Got your message. I have put you on the mailing list. Looks like I had an incorrect email for you previously.
If you're interested, you can take a look at the Colusa Groundwater Authority website for information, agendas, minutes, etc.
https://colusagroundwater.org

You will also receive the agendas via email now that I've got your correct email.
Thank you,
Mary

Mary Fahey
Water Resources Division Manager, County of Colusa
Colusa County Water Resources website
Program Manager, Colusa Groundwater Authority
colusagroundwater.org
530.458.0719

From: Ben King <bking@pacgoldag.com>
Sent: Wednesday, December 9, 2020 7:15 PM
To: Ceppos, David M <dceppos@csus.edu>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; Ben King <bking@pacgoldag.com>
Subject: Subsidence Comment

Hi David,

In the interest of time I want to submit my comment about what should be critical infrastructure for the Subsidence Indicator.

As I mentioned in a previous meeting I would suggest that our most critical infrastructure is the transportation infrastructure of I-5 and the residential infrastructure of Arbuckle including the Arbuckle cemetery. The cemetery is very close to the greatest level of subsidence and I -5 crosses adjacent to the area of greatest subsidence.

I believe we have to look at the potential for multi-feet subsidence over decades and we need to look at the subsidence potential in the context of historical events. The most significant natural disaster for the west side of California was the San Francisco earthquake which was recorded at 7.9. My concern is that continued subsidence and the occurrence of a major earthquake on the western side of the Coast Range could cause significant movement in the stream bed gravels and aquifers beneath I-5. Historically the 1906 earthquake was known to affect natural springs that stop flowing around Williams and also caused damage to the Colusa Lake Railroad which ran between Colusa to Sites from Lurline Road West and then northerly toward Sites.

This concern would also impact the Tehama Colusa Canal especially at points where it was built across gulleys in the Colusa foothills – especially since the Tehama Colusa Canal is aging infrastructure.

Thank you

Ben

From: Ben King <bking@pacgoldag.com>
Sent: Wednesday, December 9, 2020 6:31 PM
To: Ceppos, David M <dceppos@csus.edu>
Cc: Ben King <bking@pacgoldag.com>; Mary Fahey <mfahey@countyofcolusa.com>; Ben King <bking@pacgoldag.com>
Subject: Drinking Water Arsenic Contamination

Hi David,

Here is the background information about the arsenic contamination present in the drinking water systems of Grimes, Colusa and Princeton.

The Grimes contamination is documentation in the CA Arsenic Report on Page 21 – Colusa Co. WWD # 1 - 23.9 ug/L

The Colusa contamination resulted in the abandonment of two wells and one SWRCB Compliance Order in 2010 and an abandonment of a well in 2017. These wells are located at the Southern portion of the City of Colusa. The Walnut Ranch attachment refers to the 2010 Compliance Order and the Walnut Ranch Arsenic Remediation attachment.

The Princeton Arsenic level observations are referred in the Princeton Attachment. It is my understanding that the Arsenic level is approximately 18 ug/L.

I should note that groundwater quality around the Sutter Buttes has observed arsenic levels as high as 370 ug/L. This is highlighted in Figure 19 in the Sutter County Groundwater Management Plan Figures attachment. The Sutter County GMP describes the extent of the Sutter Buttes Rampart which is estimated as a 10 to 15 mile radius. This radius would include the groundwater drinking source aquafer.

Thanks for your coordination.

Best Regards,

ARSENIC IN CALIFORNIA DRINKING WATER

Three Years After EPA Notice of Noncompliance to State, Arsenic Levels Still Unsafe in Drinking Water for 55,000 Californians

ENVIRONMENTAL INTEGRITY PROJECT

SEPTEMBER, 2016

ACKNOWLEDGEMENTS

This report was researched and written by Tom Pelton, Courtney Bernhardt, and Eric Schaeffer of the Environmental Integrity Project. The map was created by Kira Burkhart and the graphics by Alana Natke.

THE ENVIRONMENTAL INTEGRITY PROJECT

The Environmental Integrity Project (http://www.environmentalintegrity.org) is a nonpartisan, nonprofit organization established in March of 2002 by former EPA enforcement attorneys to advocate for effective enforcement of environmental laws. EIP has three goals: 1) to provide objective analyses of how the failure to enforce or implement environmental laws increases pollution and affects public health; 2) to hold federal and state agencies, as well as individual corporations, accountable for failing to enforce or comply with environmental laws; and 3) to help local communities obtain the protection of environmental laws.

For questions about this report, please contact EIP Director of Communications
Tom Pelton at (202) 888-2703 or
tpelton@environmentalintegrity.org.

PHOTO CREDITS

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Arsenic in California Drinking Water

More than three years after the U.S. Environmental Protection Agency found California in noncompliance with the federal Safe Drinking Water Act, 95 community water systems in the state, serving more than 55,000 people, are still providing water with illegal levels of arsenic, according to an examination of state data for the last two years.[1] Arsenic occurs naturally in the soil and groundwater in parts of California and is a known carcinogen that may also damage the developing brains of children and cause other health problems.[2] Many of the people drinking excessive levels of arsenic are poor and/or Latino or African-American, with a cluster in the San Joaquin Valley.[3] Nearly all have been exposed to excessive arsenic levels for at least five years and probably longer.[4]

California requires public water systems to notify their customers when arsenic fails to meet federal health standards. But strangely, the state's language for mailed advisories suggests the water is still safe to drink no matter how high the contimation levels or how long they persist, with the notices telling residents: "You do not need to use an alternative water supply (e.g., bottled water)." [5] That advice conflics with what California tells private well owners (who aren't covered by federal standards) on a state website: "If you suspect that your well may have arsenic, you should not use the water until it is tested, and you take appropriate measures to protect yourself and your family from potential chronic health effects if arsenic is present."[6] Whatever the intention, California's language for people on public water systems is likely to encourage them to drink contaminated water. (For the full text of the California's language, see Appendix A). As the state continues a multi-year effort to solve the contamination problem, it should immediately fix a communications problem so that it clearly warns people not to drink arsenic-tainted tap water.

The highest levels of arsenic in drinking water in California from 2011 through 2015 were in a group home for troubled teenage boys, the Valley Teen Ranch in Madera County. About 50 boys assigned by the courts to the facility have been living in a home with water that has arsenic at concentrations averaging more than 12 times the federal limit (10 parts per billion, or ppb) over these five years, according to state records.[7] "Nobody wants to drink the water because it's brown and nasty,"said Connie R. Clendenan, CEO of the nonprofit organization that runs the group home.[8] "It looks bad."

It is bad. Although California has made substantial progress in addressing drinking water problems, the state still has 13 school districts, serving a total of 8,822 students, with arsenic in their drinking water that exceeded the federal limit from 2011 to 2015.[9] Twelve mobile home parks in California, serving 889 people, had arsenic in their tap water that averaged up to five times the legal limit. The average annual concentrations of arsenic in the drinking water of 58 residential communities (other than trailer parks) exceeded the legal limit during this time period, as did a military base, three wineries, two food preparation businesses and two campgrounds.

In many of the schools, the group home and military base, administrators say they verbally warn people not to drink tap water. They also provide bottled water as an alternative. But in the residential neighborhoods and trailer parks, it is not clear what warning – if any -- people are receiving. "There is no warning not to drink it. There is no 'non-drink' order out there," said Robert Johnson, President of the Shaver Lake Point 2 Mutual Water Company, which supplies 210 homes in Fresno County with tap water that has seven times the legal limit of arsenic. When asked if these residents should drink bottled water instead of his arsenic-tainted tap water, Johnson said: "It's one of those things, if you want to do it, that's your deal. It's not being recommended. We're not suggesting it. This is per the state of California. We are following their guidance."

The drinking water crisis in Flint, Michigan, was a reminder of how important it is for state governments to issue clear warnings to people with unhealthy tap water. California's mixed message is nearly identical to the one issued by Texas to homeowners with illegal levels of arsenic in their drinking water. Texas also tells consumers with excessive levels of arsenic: "You do not need an alternative water supply."[10] Many other states, however, are more direct in warning people not to drink water with excessive amounts of arsenic, at least for private well owners. Wisconsin, Michigan, Maine, and Washington, for example, simply tell residents not to consume water with more than 10 ppb arsenic (a health standard set by EPA in 2001). Wisconsin advises private well owners: "If your arsenic level is more than 10 ppb, the Wisconsin Department of Health Services recommends that you stop using your water for drinking or food preparation."[11] Florida advises its consumers to avoid water where arsenic contamination persists.[12] The U.S. Department of Health and Human Services makes similar recommendations.[13] If anything, the most recent science suggests that the current 10 ppb arsenic standard is not protective enough and that the IQ of children may be damaged at much lower exposures.[14]

In the wake of a 2013 EPA notice of noncompliance to California over its failure to invest enough money in its drinking water systems, the state has taken several important steps to fix its problems. Over the last three years, the state has more than doubled the amount of funding to build water treatment plants, pipelines, and new wells. The state and counties have filed compliance orders with local utilities to push them to upgrade their systems and are directing small, underfunded water systems to merge with larger utilities. Because of these measures, EPA announced in May 2016 that California was back in compliance with the federal Safe Drinking Water Act.

But in fact, the work is far from done – as witnessed by the 55,985 people in 95 communities across California who still have illegal levels of the carcinogen in their tap water, according to state records.[15] Why the delays? Local officials say that in some cases, bureaucratic negotiations are holding up projects, which are sometimes stalled because of conflicts between county and state rules. In other cases, local water districts struggle with indecision or a lack of money.

Until these important water system improvements are complete, California and EPA must do a better job of warning consumers to stop drinking water that fails federal health standards. This report recommends:

- California and EPA should revise their regulations and guidance to require that local utilities warn people to stop drinking or cooking with water that fails to meet federal arsenic standards (10 ppb), especially when the contamination persists over several years. The advice should be sensitive to the additional risks posed when children and other sensitive populations drink contaminated water. If there is no reason for consumers to take precautions, there is no reason for Safe Drinking Water Act standards in the first place.

- Public notices mailed to consumers should inform them of options for treating contaminated water at home, e.g., through filtration systems that have proven to be effective. Conversely, the public should be told what doesn't work. For example, boiling water will not reduce arsenic concentrations.

- Federal and state authorities should provide enough money to these 95 California communities to allow them to install water filtration systems or take other steps to eliminate contamination problems. Although the state has already boosted its funding, it still faces a projected $30 billion plus in needed capital improvement projects to help its inadequate systems provide safe drinking water trough 2026.[16]

The big picture is that stepped-up investment in crumbling public infrastructure is sorely needed across the U.S., and it should be regarded as a top priority for both Congress and California lawmakers. But the state also needs to improve its efforts to better inform consumers so people can protect their own health. California does not have to wait for EPA action to strengthen its warnings because the state is already empowered to act independently of EPA.

Public health advisories that are contradictory and confusing – as they are in California -- are as bad as no warnings at all, because they undermine action and weaken public confidence in government.

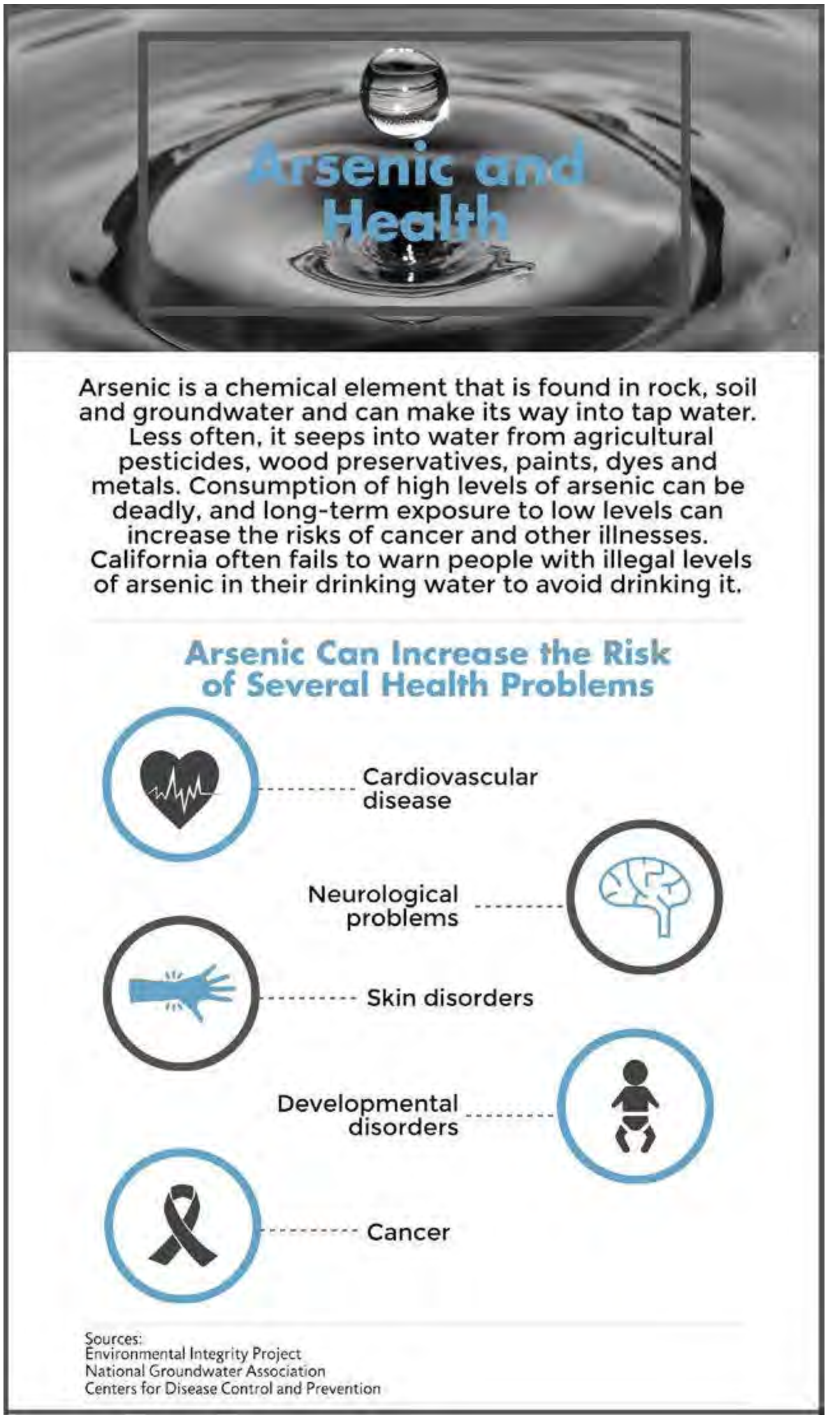
Table 1. Top 20 Arsenic Concentrations in California Public Water Systems

Water System (in Order of Arsenic Levels)	County	Pop. Served	2014-2015 avg (ppb)	2011-2015 avg (ppb)
Lakeview Improvement Association #1	Fresno	160	86.88	86.88*
Fountain Trailer Park Water	Kern	68	85.75	83.90
Hungry Gulch Water System	Kern	33	72.56	70.04
Corral De Tierra Estates WC	Monterey	45	72.50	78.40
Keeler Community Service District	Inyo	50	71.25	75.63
Quail Valley Water District- Eastside System	Kern	60	70.06	69.11
CSA 70 W-4 Pioneertown	San Bernardino	625	64.52	61.55
MD #06 Lake Shore Park	Madera	130	64.25	71.94
Valley Teen Ranch	Madera	50	62.00	120.80
Sierra East Mobile Home Community	Mono	50	54.63	47.03*
Shaver Lake Point #2	Fresno	210	52.31	42.88*
Winterhaven Mobile Estates	Los Angeles	40	52.13	53.35
Olam Spices And Vegetables Inc.	Kings	75	48.38	46.70
The Village Mobile Home Park	Los Angeles	70	45.05	47.04
Callier Water System	San Bernardino	1000	42.13	49.21*
Black Stallion Winery	Napa	25	41.75*	41.75*
Ironwood Camp	San Bernardino	1000	38.38	38.55
Boron CSD	Kern	2500	38.07	37.98
Edgewater Mobile Home Park	Sacramento	40	38.00	37.59
Prunedale MWC	Monterey	252	35.7	32.0

Note: The federal limit for arsenic is 10 ppb. * Average concentrations do not include concentrations from every year. For example, Lakeview Improvement Assn. #1 changed from a non-community water system to a community water system in 2013, and sampling data was only available from 2014 and 2015. Sampling results for Black Stallion Winery were only available for 2015. See Appendix B for annual concentrations in all systems that averaged above 10 ppb.

Health Risks Posed by Arsenic

Arsenic is a chemical element that occurs naturally in geological formations in California and elsewhere, and is also used in a variety of industrial products, including pesticides, paint, and wood preservatives.[17] It is a well-known poison at high doses. At lower doses, researchers have concluded it can cause cancers of the lung, kidney, bladder, skin, and other



organs with prolonged exposure. Any level of exposure, however, carries some risk.[18] According to EPA, the risk of developing cancer after drinking water containing 10 ppb arsenic over a lifetime is 1 in 2,000.[19] This level of risk is almost never 'acceptable' from a regulatory perspective. The agency usually tries to limit lifetime cancer risk to no more than 1 in 10,000, at most. EPA's risk estimate assumes that the cancer risk is linear, meaning if water contains 20 ppb arsenic, those who drink it over a long period of time have a 1 in 1,000 chance of developing cancer. People exposed over shorter periods of time have lower risks, but exposure during childhood may have a greater impact than exposure during adulthood.[20]

Morever, these risk calculations reflected the old thinking. New evidence suggests that the actual cancer risk may be much higher. EPA is currently revising its assessment of cancer risks from arsenic to incorporate more recent science. A 2010 draft of the assessment indicated that the risk of getting cancer from drinking water containing 10 ppb of arsenic is closer to 1 in 136, more than 17 times higher than current assumptions.[21] In addition to causing cancer, arsenic is also a neurotoxin that can harm developing brains at levels at or below the allowable limit.[22] One recent study in Maine, for example, found significant reductions in IQ and other problems in children exposed to arsenic concentrations of 5 to 10 ppb.[23] Specifically, children in homes with more than 5 ppb arsenic in the tap water tested roughly 6 points lower on a full-scale IQ test.[24] While EPA's

Scientific Advisory Board and the most recent studies suggest that the 'safe' level of arsenic is likely much lower than 10 ppb, any concentration higher than 10 is clearly unsafe.

Background on California's Problem

On April 19, 2013, EPA sent a letter to the California Department of Public Health notifying the state that it was out of compliance with the federal Safe Drinking Water Act.[25] The reason was that California's drinking water system was inadequate – providing contaminated water in many poor, rural communities – and the state was not investing enough money to fix the problem. A state investigation that year revealed that 680 community water systems serving 21 million people relied on groundwater that was compromised by one or more contaminants, with the most common being arsenic.[26]

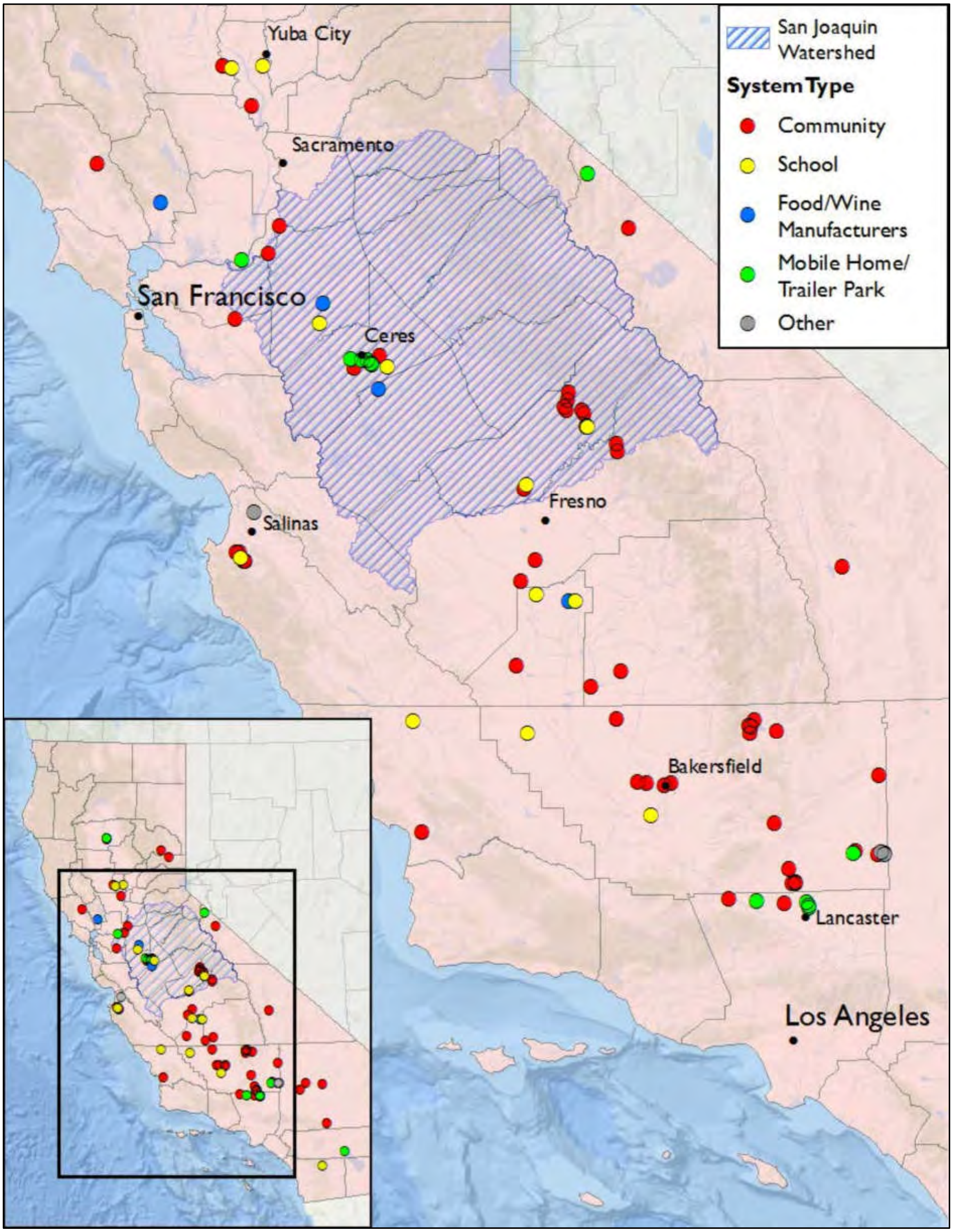
Not all of these 680 water systems provided tap water that had levels of contaminants in excess of federal health standards. In most wealthier and urban communities, the local water utilities treated the groundwater or diluted it with clean water from other wells so that it met the requirements of the federal Safe Drinking Water Act. But in 265 of these communities – often with small populations in rural, isolated areas – the tap water provided to customers had at least one violation of federal standards from 2002 to 2010 for a variety of contaminants, including nitrates from farm fertilizer, according to a 2013 report by the California Department of Health.[27]

In a separate study, researchers at the University of California, Berkeley, examined 464 community water systems serving 1.1 million people in California's San Joaquin Valley, one of the poorest regions in the state, and found that 15 percent of the systems and 14 percent of the people had tap water with arsenic above the federal limit.[28] Of the people exposed, 61 percent were either Latino or African-American. "Community water systems serving higher percentages of people of color had a 260 percent higher chance of having at least one (arsenic) violation," researcher Dr. Carolina L. Balazs and colleagues wrote.[29]

In response to the chronic drinking water problem, Congress had approved $1.5 billion to California over a decade to upgrade its water systems through a program called the Safe Drinking Water State Revolving Fund.[30] Yet because of bureaucratic obstacles and inefficiencies, the state by 2013 had not spent $455 million of those funds – the largest unspent balance of any state. According to EPA's 2013 letter of noncompliance to the California Department of Health, this violated a federal requirement that the state "make *timely* loan or grants using *all available* drinking water funds."[31]

EPA ordered the state to accelerate its efforts to fix public water systems. California Governor Jerry Brown's administration took action in several steps. These included switching control of the state's drinking water program from the Department of Health (where policy focus was dispersed among numerous problems, including drug abuse and AIDS), to the California State Water Resources Control Board (whose only focus is water) under the California Environmental Protection Agency. Since the EPA issued its

Map 1. Public Water Systems with Illegal Levels of Arsenic, 2014-2015



2013 letter of noncompliance, the state has more than doubled the amount of money it is distributing for water system upgrade projects, to an average of $738 million per year, compared to $366 million per year in the period of 2008 to 2012.[32] The unspent balance in the drinking water fund dropped to about $100 million.[33] As a result, EPA in May 2016 decided that California's system was back in compliance.[34]

Recent Analysis of California Records

The problem, however, is still far from fixed. An examination of California's online records by the Environmental Integrity Project (EIP) in May 2016 revealed that there were still 95 community water systems in the state, serving 55,985 people, providing drinking water with levels of arsenic that exceed the federal standard of 10 ppb in 2014 and 2015, according to two-year averages over those years.[35]

Over a longer period of time, 2011 through 2015, state records show 70 systems serving 46,772 residents, that each year have averaged higher than the limit in the Safe Drinking Water Act. These do not include homes on individual private wells, which are not covered by the federal Safe Drinking Water Act.

For a detailed discussion of the methods used to arrive at these numbers, please see Appendix C.

Examples of Drinking Water Contamination

Some of the worst water in community systems in California can be found in the Lakeview Community Association, which serves 160 residents in Shaver Lake (northeast of Fresno, in Fresno County). This community had an average arsenic concentration of nearly nine times the federal limit – 87 ppb – in 2014 and 2015, according to state data.[36]

Four water systems in the unincorporated community of Boron, in San Bernardino County, provided water to about 5,200 residents that had at least three times the safe limit of arsenic in 2014 and 2015.[37] In the city of Keyes in Stanislaus County, 4,891 people have tap water with arsenic concentrations that averaged above the federal limit each year for the last five years. The Pixley Public Utilities District, serving 3,310 residents, had arsenic levels in its drinking water that averaged 50 percent higher than health standards in 2011-2014.

Twelve school districts, serving a combined total of 5,462 students, had arsenic levels that averaged from 30 percent higher to three times the federal limit over the last five years. (See Table 4. Some of these school districts provided explanations, which will be discussed on pages 15 and 16 of this report).

Across California, there were 12 mobile home parks serving 889 people that had average arsenic levels ranging from 20 percent over legal limits to five times the federal standards from 2011 through 2015.[38]

Table 2: Top 10 Mobile Home Parks for Arsenic Contamination

Water System	County	People Served	2014-2015 Avg. (ppb)	2011-2015 Avg. (ppb)
Fountain Trailer Park Water	Kern	68	85.8	83.9
Sierra East Mobile Home Community	Mono	50	54.6	47.0*
Winterhaven Mobile Estates	Los Angeles	40	52.1	53.4
The Village Mobile Home Park	Los Angeles	70	45.1	47.0
Edgewater Mobile Home Park	Sacramento	40	38.0	37.6
Mitchell's Avenue E Mobile Home Park	Los Angeles	26	21.3	21.0
Millstream Mobile Home Park	Tehama	80	20.5	20.0
Country Western Mobile Home Park	Stanislaus	120	20.4	22.2
Saint Anthony Trailer Park	Riverside	300	19.7	21.5
New Orchard Mobile Home Park LLC	Tehama	125	19.6	19.0

Note: federal limit is 10 ppb arsenic. The 2011-2015 average for Sierra East Mobile Home Community reflects fewer than 5 years.

Response from California Officials

The Environmental Integrity Project asked the California State Water Resources Control Board why so many people are still exposed to contaminated drinking water after the state supposedly returned its system to compliance. Officials at the state agency replied in an interview and emails that they had issued orders to nearly all of the local utilities to fix the arsenic problem, but that some local government still need more time to upgrade their systems. In some cases, local utilities are building water filtration systems to remove arsenic, or digging new wells in an effort to extract cleaner water.

"The State Water Board Division of Drinking Water is working with each of these communities to return them to compliance," said Cindy Forbes, Deputy Director of the Division of Drinking Water at the Water Resources Board.[39] "District Office staff are working with these communities to evaluate alternative solutions, including new treatment options, new wells or modification of existing wells, and in some instances consolidation with larger water systems that can provide drinking water that meets all standards. The State Water Board is also helping communities that are struggling financially to reach compliance by offering financial assistance to solutions through low-interest loans and grants."

Public Notification of Drinking Water Violations

As the work continues to upgrade the drinking water systems, however, many citizens of California have not been given warnings to avoid drinking contaminated water.

The background is this: As part of the federal Safe Drinking Water Act, local water utilities are required to periodically test public drinking water systems that serve at least 25 people. When those results show more than 10 ppb arsenic (a standard imposed by EPA in 2001), the utilities must notify residents of the violation in writing by mail "as soon as practical, but within 30 days."[40] In California, however, the warning notices provide a mixed message, stating: "Our water system recently violated a drinking water standard," but also, "you do not need to use an alternative water supply (e.g., bottled water). This is not an emergency…. However, some people who drink water containing arsenic in excess of the (federal limit) over many years may experience skin damage or circulatory system problems, and may have an increased risk to getting cancer."[41] (For the full text of California's notice template for local utilities to use, see Appendix A)

This advisory says two contradictory things: Warning, you have a problem with your water. But don't worry – keep drinking it. If consumers are being told to ignore the federal health standards and keep drinking the contaminated water, there is no reason for the federal Safe Drinking Water standards for arsenic to exist. As stated previously in this report, California is much more clear about warning private well owners to "protect yourself and your family" from arsenic-tainted tap water. And other states – including Wisconsin, Michigan, Maine, and Washington – bluntly advise people not to drink private well water with more than 10 ppb arsenic.

In addition to receiving advisories about violations when they occur, customers also receive annual reports from their local water utilities called "Consumer Confidence Reports." These reports list the levels of more than a dozen different potential contaminants, including bacteria, lead, copper, nitrates and arsenic. When arsenic levels exceed the limit of 10 ppb, these reports provide the numbers and say: "Some people who drink water containing arsenic in excess of the MCL (maximum contaminant level) over many years may experience skin damage or circulatory system problems, and may have an increased risk of getting cancer."[42] But the reports do not tell consumers to stop drinking water with excessive levels of arsenic, and instead hint that it might not be a problem, saying: "Drinking water, including bottled water, may reasonably be expected to contain at least small amounts of some contaminants."

We asked the California State Water Resources Control Board why the agency doesn't tell people to avoid drinking water with illegal levels of arsenic. In response, Forbes, the deputy director for water, said that the state does provide this kind of blunt and immediate warning for other contaminants that can make consumers sick immediately, such as fecal bacteria. But for arsenic, she said, the threat is more long term. "Arsenic is categorized as a chronic contaminant that poses possible health risks after long-term exposure – 70-plus years of drinking two liters of arsenic-contaminated water a day above the maximum contaminant level," Forbes said. "There are no known acute/immediate health effects that would cause consumers to immediately stop drinking the water."

This answer, however, ignores the fact that many of these California residents have been drinking arsenic-contaminated water for decades. For example, Drs. Carolina Balazs and Isha Ray in 2014 published a study in the American Journal of Public Health in which they interviewed residents with contaminated tap water and found that the current notification requirements are poorly serving people with long-term exposure to pollutants.[43] "A resident from the community of Cutler explained that for years she had received Consumer Confidence Reports indicating that dibromochloropropane levels in the water exceeded the MCL (maximum contaminant level)," Balazs and Ray wrote. "These reports noted that residents should not worry because health impacts were not based on immediate exposure, but rather on lifetime exposure... She had lived in her community for nearly 30 years—so, she asked, should she worry or not? In these situations, water systems simply leave residents to cope with contaminated drinking water as best they can….In these instances, Safe Drinking Water Act regulations ultimately fail the (low-income) household."[44]

California's records identify more than 46,772 people whose tap water has had average levels of arsenic that have exceeded the federal standards for at least five years, from 2011 to 2015. But there is no reason to believe that these people received cleaner water before this. The longer a person drinks water contaminated with excessive levels of arsenic, the higher the increased risk of cancer. In much the same way, smoking a single cigarette is not an immediate health threat, in that it will instantly kill a person. But the longer a person smokes, the worse the health threat. For this reason, California would better protect public health if it told people to stop drinking arsenic-tainted water now, just as health warnings on tobacco required by the U.S. Food and Drug Administration advise, "WARNING: Quitting smoking now greatly reduces serious risks to your health." These advisories do not state, "WARNING: You do not need to change your smoking habits."

Evolution of the Science on Arsenic

One reason for stronger warning language is that scientific research continues to show that arsenic causes health problems – including brain damage in children -- at lower levels than previously thought.

The history of EPA's arsenic rule reflects the continuing evolution of scientific knowledge about the harms that even low levels of the element can cause. Back in 1996, Congress amended the Safe Drinking Water Act and directed EPA to establish new limits for arsenic to replace the old standard of 50 ppb. Based on the best available research, EPA proposed a limit of 5 ppb in 2000. Because arsenic is a carcinogen, some public health experts consider any level above zero to pose some risk. EPA then revised its proposal, based in part on cost considerations, and finalized a new arsenic standard of 10 ppb in 2001.

The EPA Administrator at the time, Christine Todd Whitman, explained that "the 10 ppb protects public health based on the best available science and ensures that the cost of the standard is achievable."[45] The new regulations required that public water systems across the U.S. meet the new standard by January 23, 2006.[46] The law allowed states to grant exemptions until January 23, 2015, for some small community water systems that had trouble complying.[47]

The 2014 Maine study discussed earlier in this report found found significant reductions in IQ in children exposed to arsenic concentrations of 5 to 10 ppb.[48] With this new information, EPA should change its own guidance for notification language so that people – especially parents of young children -- receive a clearer warning not to drink contaminated water. A template for warning language on the federal agency's website for drinking water systems with chemical contaminants such as arsenic advises utilities to tell their customers: "Some people who drink water containing arsenic in excess of the MCL (maxiumum contaminant level) over many years may have an increased risk of getting cancer." But the notices also say: "There is nothing you need to do….If you have specific health concerns, consult your doctor."[49] This is a problem, because many lower-income people do not have doctors with whom they can regularly consult about questions like water quality.

Responses from Local Drinking Water Systems

When asked about their drinking water violations by EIP, some of the utilities in California with illegal levels of arsenic replied that their attempts to fix the problem have been hindered by bureaucratic obstacles at the local level. Others indicated they are taking steps to solve the problem, but simply need more time or money. Not all public systems were contacted by EIP or provided answers.

Table 3. Top 10 Residential Water Systems for Arsenic Contamination (Excluding Mobile Home Parks)

System	County	Population Served	2014-2015 avg (ppb)	2011-2015 avg. (ppb)
Lakeview Improvement Association #1	Fresno	160	86.9	86.9*
Corral De Tierra Estates WC	Monterey	45	72.5	78.4
Keeler Community Service District	Inyo	50	71.3	75.6
Quail Valley Water District-Eastside System	Kern	60	70.1	69.1
MD #06 Lake Shore Park	Madera	130	64.3	71.9
Valley Teen Ranch	Madera	50	62.0	120.8
Shaver Lake Point #2	Fresno	210	52.3	42.9
Boron Community Service District	Kern	2500	38.1	38.0
Monterey Park Tract Comm. Service District	Stanislaus	186	31.9	34.3
North Edwards Water District	Kern	600	31.5	31.6

Note: The federal limit is 10 ppb arsenic. Lakeview had fewer than five years of data available.

At the **Lakeview Improvement Association** in Fresno County, 160 people have been receiving drinking water with more than eight times the legal limit of arsenic on average for at least the last five years, according to state data. State records show that on May 16, 2016, the California Water Resources Control Board issued a citation to the association's water system, imposing a fine of $1,000 for its failure to follow the directives of two earlier compliance orders, in 2014 and 2015. "The water system continues to violate the arsenic maximum contaminant level (MCL) and does not appear to be making progress toward the compliance deadline," says the most recent letter from the state. "Additionally, the water system has failed to routinely conduct the public notification of the arsenic MCL violation, as required."

Philip Dutton, an engineer for surrounding Fresno County, said that the Lakeview Association's plan, as expressed verbally, is to test some in-home water filtration systems and see how well they perform.[50] "They've got a few of these (filtration systems) installed in homes, but they are sampling from different technologies to try and identify what is going to be the best long-term alternative," Dutton said. The California State Water Resources Control Board's website already lists which types of filtration technologies work well to remove arsenic.[51]

In **Kettleman City**, in Kings County, 1,450 residents have had tap water with excessive levels of arsenic for decades. The average from 2011 to 2015 was 20 percent above the legal limit, according to state data. "I have a daughter, a little one, who's still brushing her teeth with contaminated water, taking a bath in contaminated water," said Maricela Mares-Alatorre, a city resident, during a recent public hearing of the state water board.[52] The Kettleman City Community Services District has promised local residents that it will build a $9 million water treatment plant, but the project has been repeatedly delayed – with a target to open in the fall of 2016 recently pushed back to 2018.[53]

At the **Corral De Tierra Estates** subdivision in Monterey County, 45 people have been exposed to drinking water with arsenic levels almost eight times the legal limit from at least 2011 through 2016, state records indicate. This small water system has received 10 violations notices from the state for excessive levels of arsenic over the last decade, with the most recent in the first quarter of 2016, when it had 77 ppb of the contaminant (compared to the 10 ppb limit).

The manager of Monterey County's drinking water program, Cheryl Sandoval, said Corral De Tierra Estates is among at least five privately-owned water systems that have been issued corrective orders by the county because they are in violation of the arsenic standard. Solving the problem is taking longer than expected, Sandoval said, and some of the local water utilities are still debating the best path forward. "Dealing with the problem is very complicated," Sandoval said.[54] "They haven't made a lot of progress toward compliance, but they are going to have to." One challenge is that a water treatment plant for even a small system can cost hundreds of thousands of dollars and cause new waste disposal problems, because the plants produce concentrated arsenic sludge that must be handled carefully as a hazardous material. Corral De Tierra Estates and other subdivisions want to try in-home water treatment systems as a systemic solution, but county rules don't allow that, Sandoval said. However, debate over this in-home option continues, because new state regulations may open the door for in-home filtration as a systemic solution in the future.

Meanwhile, as the bureaucratic discussions continue, residents are receiving confusing advice about whether they should drink the water pouring from their taps with illegal levels of arsenic. One recent report from Corral de Tierra Estates to local water consumers, displayed on the state website and sent to homeowners in July 2014, advised people that arsenic levels were eight times above the legal limit.[55] But that fact was buried in the middle of a dense report with lots of numbers that also gave the impression that the exceedance was not a problem. The report told homeowners: "The presence of contaminants does not necessarily indicate that the water poses a health risk."[56]

At the **Quail Valley Water District-Eastside System** in Kern County, 60 residents have been receiving drinking water with seven times the legal limit of arsenic over the last five years, state records show. In April 2015, the state issued a compliance order to the local utility and mandated that it fix the problem by April 2018.

Randy Hardenbrook, Director of the Quail Valley Water District, said the problem should be solved within the next two years because a $5.8 million grant from the state is allowing the district to build a new pipeline. The pipe will be about 8.5 miles long and will connect a part of the system with arsenic-tainted water to a well that has good water.[57] In the interim, local residents receive quarterly letters with data on the arsenic exceedances but are not being provided with bottled water. More importantly, they are not being told to refrain from consuming the contaminated water. "We're not telling them not to drink it," Hardenbrook said, "but we are telling them there are long-term health effects."[58]

At the **Shaver Lake Point #2** subdivision in Fresno County, 210 people have been receiving tap water with more than four times legal levels of arsenic for at least the last five years, according to state data. In January 2015, the state wrote to the water system's administrators and ordered them to come into compliance with the federal and state arsenic limits by December 31, 2016.

With only four months left until the deadline, the arsenic levels remain illegally high and Robert Johnson, President of the Shaver Lake Point Mutual Water Company, said he is still thinking about what to do about the problem.[59] "Currently, it's being researched. We have engineers involved. We have water experts involved, and we are trying to figure it out," Johnson said. He added that building a water filtration system could cost as much as $250,000, so the subdivision is considering trying to blend water from its arsenic-tainted wells with cleaner water from different wells.

Meanwhile, nobody in the community is being warned to avoid the contaminated water. "There is no warning not to drink it. There is no 'non-drink' order out there," said Johnson.[60] When asked if his customers should drink bottled water as a precaution instead of the arsenic-tainted tap water, Johnson said: "It's one of those things, if you want to do it, that's your deal. It's not being recommended. We're not suggesting it. This is per the state of California."

Group Home for Troubled Children

The **Valley Teen Ranch**, a Christian residential treatment group home for 32 court-referred abused and neglected boys in Madera County, has arsenic in its tap water that averaged more than 12 times the federal limit from 2011 through 2015, according to state records.[61] "We've been out of compliance, but no children have gotten sick, no adults have gotten sick," said Connie R. Clendenan, CEO of the nonprofit organization that runs the group home. "Nobody wants to drink the water here because it's brown and nasty."[62]

About five years ago, the state approved a $5 million grant to help the group home solve the problem by linking its small water system to a larger one run by the county. But the work has not started yet. Because of ongoing negotiations at the county level, the fix could still be three years or more away, Clendanan said. Meanwhile, children are being given bottled water and are verbally warned not to drink tap water, although there are no warning signs posted above sinks.

"I want to get out of the water business. I'm in the kid business," Clendenan said. Of the continuing delays in fixing the problem with contaminated water, she said: "Nobody's mad. But it's government, and it takes a lot of time. It's just the stupid county."

Table 4. Schools with Excessive Arsenic in Drinking Water

System	County	Population Served	2014-2015 avg. (ppb)	2011-2015 avg. (ppb)
Kit Carson Elem. School	Kings	510	34.7	34.7*
Washington School WS	Monterey	250	26.1	27.7
MUSD-Nile Garden School	San Joaquin	804	20.9	22.8
Liberty High School	Madera	1340	17.9	20.5*
Island Union School	Kings	300	11.9	18.8
Winship Elementary School	Sutter	38	16.4	17.3*
Lakeside School	Kern	800	16.3	16.9
Barry Elementary School	Sutter	650	15.2	15.3
Pleasant Valley Elementary	San Luis Obispo	100	13.8	14.1
Gratton School	Stanislaus	110	13.5	13.5
North Fork Union School	Madera	350	12.9	12.4
Warner Unified School District	San Diego	250	10.9	11.4
Central Union Elementary	Kings	320	10.1	13.5

*Note: federal limit is10 ppb arsenic. *Indicates systems with monitoring gaps (less than five years available data)*

Arsenic in School Drinking Water

At the **Washington School in Salinas,** California, the tap water serving about 250 students has had almost three times the federal limit of arsenic for the last five years, 28 ppb on average over this time period, compared to the limit of 10 ppb.[63] School Principal Whitney Meyer said that the local school district has been discussing the problem for several years but does not yet have a solution. Meanwhile, students are given bottled water, she said.

"We remind them over and over that they cannot drink the water," Meyer said.[64] "Many of the students live out in this area and their homes are similarly impacted (with arsenic), so they also hear the message at home. We have drinking stations with clean water in every classroom, teaching space, and hallway. The fountains have all been shut down."

At the **Barry Elementary School in Yuba City**, California, the arsenic levels have averaged 50 percent above the federal limit for arsenic over the last five years. Because of the violations, the state issued a compliance order to the school in May 2015. Tom Butcher, Director of Maintenance and Facilities for the school system, said that the school has not yet solved the problem, but is giving bottled water to students as officials try to figure out a solution.[65] Adminstrators of the water system are discussing a consolidation with a larger neighboring system that has better water. "The (state) Water Board indicates a best case scenario of a consolidation in approximately 1.5 years," Butcher said. "Until the consolidation is completed (the school district) will continue to provide bottled drinking water."

At the **Kit Carson Elementary School**, in Hanford, Ca., arsenic levels in drinking water averaged more than three times the legal limit in 2011 through 2014, according to state records. In January 2015, the school solved the problem by connecting its pipes to the water system of the surrounding city,[66] whose arsenic levels are below the federal limits.

At the **Lakeside School in Bakersfield,** California, the arsenic levels in the drinking water averaged more than 70 percent above the federal limit for arsenic over the last five years, 17 ppb compared to the limit of 10 ppb. Ty Bryson, District Superintendent, said that the school notified all families by sending home notice letters with the students and by posting warnings in the office. "We provide bottled drinking water for students and staff," Bryson said. "We drilled an alternate well, but that also had unacceptable levels of contaminant. We are now pursuing an alternative source of drinking water by connecting to a local municipal water source via pipeline."

At the **Gratton School in Denair,** California, the drinking water system has had arsenic levels that averaged 40 percent above the federal limit for arsenic over the last five years, state records indicate. The school's superintendent, Shannon Sanford, said that students have been provided bottled water for the last two years. "Students were initially warned (not to drink the water) and signs were used until fountains were disabled," Sanford said. More recently, the school drilled a new well that will be used for the 2016-2017 school year that should solve the problem.

At the **Island Union School in Lemoore,** California, arsenic levels in the drinking water were nearly twice the federal limit from 2011 to 2015, averaging 18.8 ppb compared to federal limit of 10 ppb, according to state records. Superintendent Charlotte Hines said the school dug a new well in 2015, and provided students and warnings and bottled water in the interim. "We know that bottled water is only a temporary solution," Hines said. "And in an effort to find a permanent solution, the school requested -- and was awarded -- state funding to drill a new well that would meet all primary drinking water standards."[67]

Military Base with Contaminated Water

At the **U.S. Army Base Fort Irwin** in San Bernardino County, 16,000 soldiers live in facilities that have had arsenic in some tap water at levels 50 percent higher than the federal limit from 2011 through 2015, state records indicate. For the last three years, the Army Corps of Engineers has been building a new $100 million water treatment plant at the base to solve the problem. The plant is now undergoing testing and is scheduled to go online in October 2016, base officials indicate.

"The new plant will treat all Fort Irwin water to comply with Safe Drinking Water act Standards for ALL pollutants of concern including …arsenic," said Muhammad A. Bari, Director Public Works at Fort Irwin.[68]

In the interim, soldiers have been provided with bottled water and warned which faucets to avoid, according to base managers.

Vineyards with High Arsenic Levels

In San Joaquin County, the **Delicato Family Vineyards** had arsenic levels in the tap water that averaged 18 ppb from 2011 through 2014, which was 80 percent higher than the federal limits, state records indicate. Kylie Barnett, a spokeswoman for the company, said that the vineyards worked with county officials in 2014 to build a new drinking water system, including by digging two new wells, which brought the arsenic levels down below the federal standard in 2015 and 2016.[69] "The drinking water is not used in production of our wine," Barnett noted. Before the repair, people working at the vineyards and visiting were provided bottled water, she said.

In Napa County, the **Larkmead Vineyards** had drinking water with six times more arsenic than allowed from 2011 through 2013, according to state records. No results were listed for 2014 or 2015, and it is unclear if the drinking water system, which serves 25 people, is used for workers or guests. (Wine making does not generally use tap water.) Emails sent to managers of the vineyard asking about the water were not returned. The researchers of this report also received no response from the **Black Stallion Winery** in Napa County, whose tap water had four times legal limits of arsenic from 2011 through 2015, according to state records.

Conclusion

California is making progress toward solving its drinking water contamination problem. The state has reorganized its drinking water agency, and increased its financial assistance to local utilities to build water treatment systems, dig new wells, and take other steps to resolve the issue. The work, however, is expected to take many more years. In the meantime, tens of thousands of people continue to be exposed to drinking water with illegal levels of arsenic, a carcinogen that could damage the developing brains of children and cause other health problems. And yet, the warnings that some of these residents receive from the government are contradictory and confusing.

Both California and the federal government need to do more to protect consumers, especially the young. This report recommends:

1) California and EPA should both revise the language for written notifications of violations of arsenic standards, so that people are clearly advised to stop drinking contaminated water. If the violations are in schools or group homes, warning signs should also be posted over all sinks and drinking fountains. The state should help provide bottled water as an interim solution.

2) Consumers should be provided more information through the mail about what works and what does not work to remove arsenic from tap water. Residents need to know, for example, that boiling water will not help, but that certain filtration systems can remove the carcinogen. In some cases, residents may need technical help from the state in understanding how to use filtration systems properly.

3) Both Congress and the state government should increase investments in upgrades to California's drinking water systems. This is not only an environmental justice issue, but also a sensible strategy to boost the local economy through the hiring of engineers, construction workers and others to improve local infrastructure.

Counter arguments made by California officials – that the state is already taking action, and that arsenic is not an immediate threat to public health – do not hold water. Although the state has issued enforcement orders to local utilities, some local officials clearly still need more prodding and money to upgrade their water systems. A growing amount of scientific research suggests that arsenic increases the risk of cancer and other diseases and may do so at a lower level than expressed in current federal regulations. Years more of exposure to arsenic-tainted water will only raise the risk of cancer or neurological damage for California residents.

The state and federal governments should advise people to stop drinking contaminated water immediately, just as public health experts urge smokers to change their habits sooner rather than later because it will increase their odds of survival.

With public health warnings, simple and direct is better than bureaucratic and complex, because safe is better than sorry when people's lives and minds are at risk.

APPENDIX A: California's Language for Public Notices about Arsenic Violations

IMPORTANT INFORMATION ABOUT YOUR DRINKING WATER

Este informe contiene información muy importante sobre su agua potable.
Tradúzcalo o hable con alguien que lo entienda bien.

[System] Has Levels of Arsenic Above the Drinking Water Standard

Our water system recently violated a drinking water standard. Although this is not an emergency, as our customers, you have a right to know what you should do, what happened, and what we are doing to correct this situation.

We routinely monitor for the presence of drinking water contaminants. Water sample results received on [date] showed arsenic levels of [level and units]. This is above the standard, or maximum contaminant level (MCL), of 0.010 milligrams per liter.

What should I do?

- **You do not need to use an alternative water supply (e.g., bottled water).**
- This is not an emergency. If it had been, you would have been notified immediately. However, *some people who drink water containing arsenic in excess of the MCL over many years may experience skin damage or circulatory system problems, and may have an increased risk to getting cancer.*
- If you have other health issues concerning the consumption of this water, you may wish to consult your doctor.

What happened? What is being done?

[Describe corrective action]. We anticipate resolving the problem within [estimated time frame].

For more information, please contact [name of contact] at [phone number] or [mailing address].

Please share this information with all the other people who drink this water, especially those who may not have received this notice directly (for example, people in apartments, *nursing homes, schools, and businesses). You can do this by posting this public notice in a public place or distributing copies by hand or mail.*

Secondary Notification Requirements

Upon receipt of notification from a person operating a public water system, the following notification must be given within 10 days [Health and Safety Code Section 116450(g)]:

- SCHOOLS: Must notify school employees, students, and parents (if the students are minors).
- RESIDENTIAL RENTAL PROPERTY OWNERS OR MANAGERS (including nursing homes and care facilities): Must notify tenants.
- BUSINESS PROPERTY OWNERS, MANAGERS, OR OPERATORS: Must notify employees of businesses located on the property.

This notice is being sent to you by [system].

State Water System ID#: ___________. Date distributed: ___________.

APPENDIX B: Listing of All California Public Drinking Water Systems with Arsenic Levels that Averaged Over the Federal Limit over the Last Five Years

System Name	County	Pop. Served	2014-2015 Avg (ppb)	2011-2015 Avg (ppb)	
Lakeview Improvement Association #1	Fresno	160	86.9	86.9	^
Fountain Trailer Park Water	Kern	68	85.8	83.9	*
Hungry Gulch Water System	Kern	33	72.6	70.0	*
Corral De Tierra Estates WC	Monterey	45	72.5	78.4	*
Keeler Community Service District	Inyo	50	71.3	75.6	*
Quail Valley Water District-Eastside System	Kern	60	70.1	69.1	*
CSA 70 W-4 Pioneertown	San Bernardino	625	64.5	61.6	*
MD #06 Lake Shore Park	Madera	130	64.3	71.9	*
Valley Teen Ranch	Madera	50	62.0	120.8	*
Sierra East Mobile Home Community	Mono	50	54.6	47.0	^
Shaver Lake Point #2	Fresno	210	52.3	42.9	^
Winterhaven Mobile Estates	Los Angeles	40	52.1	53.4	*
Olam Spices And Vegetables Inc.	Kings	75	48.4	46.7	*

System Name	County	Pop. Served	2014-2015 Avg (ppb)	2011-2015 Avg (ppb)	
The Village Mobile Home Park	Los Angeles	70	45.1	47.0	*
Callier Water System	San Bernardino	1000	42.1	49.2	^
Black Stallion Winery	Napa	25	41.8	41.8	^
Ironwood Camp	San Bernardino	1000	38.4	38.6	*
Boron CSD	Kern	2500	38.1	38.0	*
Edgewater Mobile Home Park	Sacramento	40	38.0	37.6	*
Prunedale MWC	Monterey	252	35.7	32.0	
Kit Carson Elem. School	Kings	510	34.7	34.7	^
Darr Water Co.	San Bernardino	1000	34.3	36.0	*
Monterey Park Tract Community Service District	Stanislaus	186	31.9	34.3	*
North Edwards WD	Kern	600	31.5	31.6	*
Desert Lake Community Service District	Kern	700	31.0	32.5	*
Locke Water Works Co [SWS]	Sacramento	80	29.5	29.1	*
Lucky 18 On Rosamond, LLC.	Kern	73	28.0	24.3	*
Washington School WS	Monterey	250	26.1	27.7	*
Rancho Marina	Sacramento	250	24.0	30.1	*
Colusa Co. WWD #1 - Grimes	Colusa	500	23.9	24.7	*
Bridgeport PUD	Mono	850	23.3	24.0	*
Country Hills Estates	San Luis Obispo	60	23.0	26.8	^
Doubletree Ranch Water System	Contra Costa	49	21.6	22.4	*
Mitchell's Avenue E Mobile Home Park	Los Angeles	26	21.3	21.0	*
Vista Del Toro WS	Monterey	87	21.0	20.4	*
MUSD-Nile Garden School	San Joaquin	804	20.9	22.8	*
Country Villa Apts.	Stanislaus	30	20.8	21.1	*
Millstream Mobile Home Park	Tehama	80	20.5	20.0	*
Country Western Mobile Home Park	Stanislaus	120	20.4	22.2	*
Saint Anthony Trailer Park	Riverside	300	19.7	21.5	*
New Orchard Mobile Home Park LLC	Tehama	125	19.6	19.0	*
MD #24 Teaford Meadow Lakes	Madera	150	19.0	12.5	
William Fisher Memorial Water Company	Kern	53	19.0	18.4	*
Ceres West Mobile Home Park	Stanislaus	161	18.9	18.0	*
Boulder Canyon Water Association	Kern	28	18.4	17.9	*
Lakeview Ranchos Mutual Water Company	Kern	120	18.1	22.4	*
Liberty High School	Madera	1340	17.9	20.5	^
Sutter Co. WWD #1 (Robbins)	Sutter	350	17.9	18.1	*
MD #42 Still Meadow	Madera	100	17.7	17.7	^
Maher Mutual Water Company	Kern	150	17.7	20.8	*
Cedar Valley Mutual Water Co.	Madera	137	17.6	18.6	^
First Mutual Water System	Kern	35	17.5	15.1	*
Sierra Co. W.W.D #1 Calpine	Sierra	225	17.0	14.1	*
Bar-Len MWC	San Bernardino	124	16.6	16.2	*

System Name	County	Pop. Served	2014-2015 Avg (ppb)	2011-2015 Avg (ppb)	
Winship Elementary School	Sutter	38	16.4	17.3	^
Lakeside School	Kern	800	16.3	16.9	*
Lanare Community Services Dist	Fresno	660	16.2	17.3	*
Delicato Vineyards	San Joaquin	25	15.6	18.3	^
Fourth Street Water System	Kern	56	15.6	14.0	*
Barry Elementary School	Sutter	650	15.2	15.3	*
Rand Communities Water District	Kern	450	15.1	15.3	*
US Army Fort Irwin	San Bernardino	16000	14.9	15.4	*
Pond Mutual Water Company	Kern	48	14.7	14.4	^
Alpaugh Community Services District	Tulare	1026	14.5	17.8	
Lands Of Promise Mutual Water Associatio	Kern	190	14.4	15.0	*
Pixley Public Util Dist	Tulare	3310	14.4	15.0	*
Caruthers Comm Serv District	Fresno	2497	14.3	15.4	*
Nord Road Water Association	Kern	32	14.2	15.0	*
Lancaster Park Mobile Home Park	Los Angeles	53	14.2	15.0	*
Mesa Del Toro MWC	Monterey	90	14.2	13.1	*
Green Run Mobile Estates	Stanislaus	100	14.0	15.1	*
Pleasant Valley Elementary	San Luis Obispo	100	13.8	14.1	*
Loch Haven Mutual Water Company	Sonoma	50	13.8	13.1	*
Gratton School	Stanislaus	110	13.5	13.5	*
Hillview Water Co-Raymond	Madera	290	13.4	17.8	
Mettler Valley Mutual	Los Angeles	100	13.0	13.1	*
Mobile Plaza Park	Stanislaus	125	13.0	12.7	*
Hilmar Cheese Company	Merced	1000	13.0	13.3	
North Fork Union School	Madera	350	12.9	12.4	*
Yosemite Forks Est Mutual	Madera	110	12.8	11.6	
MD #08 North Fork Water System	Madera	264	12.8	13.9	^
Keyes Community Services Dist.	Stanislaus	4891	12.3	12.8	*
Countryside Mobile Home Park	Stanislaus	60	12.1	12.5	*
Land Project Mutual Water Co.	Los Angeles	1500	12.1	13.5	*
El Adobe POA, Inc.	Kern	200	12.1	12.1	*
Island Union School	Kings	300	11.9	18.8	
Plumas Eureka CSD	Plumas	325	11.6	11.4	*
Kettleman City CSD	Kings	1450	11.4	12.0	*
Laguna Seca WC	Monterey	162	11.1	11.7	*
Los Molinos Comm. Services Dist.	Tehama	1500	11.1	9.0	
R.S. Mutual Water Company	Kern	67	11.0	11.1	*
Oasis Property Owners Association	Kern	100	10.9	10.8	^
Warner Unified School District	San Diego	250	10.9	11.4	^
MD #07 Marina View Heights	Madera	200	10.5	9.3	
Central Union Elementary	Kings	320	10.1	13.5	^

Note: Click on the hyperlink in the name of the system to view the state records for each water system.

** Indicates a system that has had annual concentrations averaging over the federal limit (10 ppb) each year 2011-2015*

^ Indicates that the 2011-2015 average includes years for which data was not available.

APPENDIX C:

Methods

This report is based on public data available from the California Environmental Protection Agency's State Water Resources Control Board (SWRCB) as of May 2016. We downloaded the SWRCB's Water Quality Analyses Database Files for 2011-2016 and identified public water systems that had arsenic concentrations that exceeded the 10 ppb Maximum Contaminant Level, targeting the systems with frequent exceedances between 2011 and 2015. The SWRCB database contained results for each water source used by a drinking water system, such as wells, treated or blended water, and standby wells that are only allowed to be used for a few days during a year. SWRCB warns users of its database that results in the database may not reflect the quality of water that systems actually served their customers.

Calculating average arsenic concentrations

- We calculated the average arsenic concentration from each individual water source at each water system using the sampling results available in SWRCB's database as of May 2016. Some sampling results from the end of 2015 may not have been available in the database at the time we downloaded the data in May.

- We reviewed each water system's source descriptions to determine which sources represented water served to consumers and whether the source should be included in the system-wide average arsenic concentration. For example, if the database showed that a system had two groundwater wells and a 'treated' source, we assumed that consumers would be served the treated source if results for that treated source were available each year. If the database listed a treated source in 2011, for example, but contained no data from that source for the following years, we excluded that source from the average because it was not clear if the system continued treating water for arsenic. If a system listed a source as inactive or as a 'standby' option, we excluded that source from the analysis because we could not determine when or if the water was used. We compared the selected sources with available Consumer Confidence Reports available through California's Drinking Water Watch system and narrative information in public SWRCB enforcement action documents to verify, to the extent possible, that the sources we selected represented water that was provided to consumers. If no information was available for a particular system, we relied on the assumptions described above (i.e. inactive and standby sources were not used, treated sources were used instead of untreated sources when concentrations were available for each year). We did not include purchased water sources.

- After identifying individual sources, we calculated the system's annual average arsenic concentration using the annual average concentrations from each source. The average concentrations during the two-year period between 2014 and 2015 and the five year period between 2011 and 2015 are time-weighted average concentrations (i.e. we averaged the annual average concentrations from each year). This method is similar to how the California EPA's Office of Environmental Health Hazard Assessment calculated average concentrations at drinking water systems for use in it's 2014 CalEnviroScreen 2.0 tool, except we focused on annual average concentrations from 2011-2015, rather than a single average concentration from 2005-2013.

- We excluded entire systems from the analysis if a) they were inactive, b) the available data and source descriptions did not allow us to confidently assume that customers received the sampled water at their taps, and c) the average concentration over the most recent two years (2014-2015) fell below the MCL.

Mapping Public Water Systems

To map water system locations, we found the centroids of public water system boundaries from the California Environmental Health Tracking Program's Water Systems Geographic Reporting Tool, or Water Boundary Tool (WBT). For systems without boundaries in the WBT, we determined coordinates from the addresses in the SWRCB Water Quality Analysis database files and the California Drinking Water Watch system.

Notes

[1] Based on averages for 2014-2015. Numbers in this report from the California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed May, 2016.

[2] U.S. EPA (1998), Integrated Risk Information System, Inorganic Arsenic, available at http://www.epa.gov/iris/subst/0278.htm.

[3] Carolina L. Balazs, Rachel Morello-Frosch, Alan E. Hubbard and Isha Ray, "Environmental justice implications of arsenic contamination in California's San Joaquin Valley: a cross-sectional, cluster-design examining exposure and compliance in community drinking water systems," Environmental Health, 2012. Link: https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-11-84

[4] California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed May. Records show 51,306 residents receiving drinking water from 2011-2015 with annual averages of more than 10 ppb.

[5] California Code of Regulations Title 22, Chapter 15, Section 64463.4(b)] reglations require notifications for arsenic exceedances. The California State Water Resources Board template for the language in notifications to be sent out by local water utilities is available on state agency's website at: http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/Notices.shtml.

[6] California State Water Resources Control Board website, link: http://www.waterboards.ca.gov/drinking_water/certlic/device/watertreatmentdevices.shtml
[7] Ibid.
[8] Telephone interview with Connie R. Clendenan, CEO of the Valley Teen Ranch nonprofit organization, on August 1, 2016.
[9] Ibid.
[10] Texas Commission on Environmental Quality Notice of Drinking Water Arsenic Violation. Available at https://www.tceq.texas.gov/assets/public/permitting/watersupply/pdw/notices/chemical/arsenic.pdf
[11] Wisconsin Department of Natural Resources, Arsenic, Available at: http://dnr.wi.gov/topic/groundwater/arsenic/, accessed 3/7/2016.
[12] Florida Department of health, Brueau of Environmental Health, "Chemicals in Private Drinking Water Wells Fact Sheet- Arsenic," Available at: http://www.floridahealth.gov/environmental-health/drinking-water/_documents/arsenic-fs.pdf. Accessed 3/7/2016.
[13] See e.g. U.S. Department of Health and Human Services, (2004), "Health Consultation: Arsenic in Private Drinking Water Wells, Cornville, Yavapai County, Arizona," available at: http://www.atsdr.cdc.gov/HAC/pha/ArsenicInPrivate061504-AZ/ArsenicInPrivateHC061504.pdf, accessed 3/8/2016.
[14] Wasserman et al. (2014), A Cross-Sectional Study of Well Water Arsenic and Child IQ in Maine Schoolchildren, Environ Health 13:23-32.
[15] Based on averages for 2014-2015. Numbers from California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed July 28, 2016.
[16] Letter from Jared Blumenfeld, Director of EPA's Region 9 office, to California Department of Public Health Director Dr. Ron Chapman, April 19, 2013. Link: https://www3.epa.gov/region9/water/grants/pdf/CDPHNoticeofNonCompliance.pdf
[17] U.S. Centers for Disease Control, fact sheet on arsenic. Available at http://www.cdc.gov/biomonitoring/pdf/Arsenic_FactSheet.pdf
[18] U.S. EPA (1998), Integrated Risk Information System, Inorganic Arsenic, available at http://www.epa.gov/iris/subst/0278.htm.

[19] The EPA describes arsenic's cancer-causing potency with a 'slope factor' (because it describes the slope of the dose-response curve). The current EPA slope factor for arsenic is 1.5 per mg/kg-d. This number represents the risk that can be expected from consuming one milligram of arsenic per kilogram of body weight per day. The EPA also translates the slope factor into a 'drinking water unit risk' of 5×10^{-5} per µg/L. For carcinogens, the formal MCL Goal is always zero. Zero is an unattainable goal, so in most cases the EPA will reduce exposure to carcinogens to a level of 'acceptable risk,' something between 10^{-6} (1 in 1,000,000) to 10^{-4} (1 in 10,000).[19] One way of looking at this range is to assume that risks less than 1 in 1,000,000 are always 'acceptable,' while risks greater than 1 in 10,000 never are. The risks of drinking arsenic at the MCL of 10 µg /L are much higher than 1 in 10,000.

[20] See, e.g., National Research Council, Critical Aspects of EPA's IRIS Assessment of Inorganic Arsenic – Interim Report, 82 – 83 (2013). For health endpoints like childhood IQ, the critical window of exposure is obviously much less, encompassing in utero development and childhood.

[21] EPA web page, "Drinking Water Arsenic Rule History," available at: https://www.epa.gov/dwreginfo/drinking-water-arsenic-rule-history.
[22] ATSDR (2007), Toxicological Profile for Arsenic; Grandjean and Landrigan (2014), Neurobehavioural Effects of Developmental Toxicity, *Lancet Neurol* 13:330-338.

[23] Wasserman et al. (2014), A Cross-Sectional Study of Well Water Arsenic and Child IQ in Maine Schoolchildren, *Environ Health* 13:23-32.

[24] Ibid.

[25] Ibid.
[26] California Water Resources Board report to the California legislature, "Communities that Rely on a Contaminated Groundwater Source for Drinking Water," January 2013. Link: http://www.waterboards.ca.gov/water_issues/programs/gama/ab2222/docs/ab2222.pdf
[27] California Water Resources Board report to the California legislature, "Communities that Rely on a Contaminated Groundwater Source for Drinking Water," January 2013. Link: http://www.waterboards.ca.gov/water_issues/programs/gama/ab2222/docs/ab2222.pdf
[28] Carolina L. Balazs and colleagues, "Environmental Justice Implications of Arsenic Contamination In California's San Joaquin Valley: a Cross-Sectional, Cluster-Design Examining Exposure and Compliance in Community Drinking Water Systems," Environmental Health, November 14, 2012. Link: https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-11-84
[29] Ibid.
[30] Letter from Jared Blumenfeld, Director of EPA's Region 9 office, to California Department of Public Health Director Dr. Ron Chapman, April 19, 2013. Link: https://www3.epa.gov/region9/water/grants/pdf/CDPHNoticeofNonCompliance.pdf
[31] Ibid.
[32] California Water Boards press release, "State Water Board, Drinking Water Revolving Fund Return to Safe Drinking Water Act Compliance," May 26, 2016. Link: http://www.waterboards.ca.gov/press_room/press_releases/2016/pr052616_cap_release.pdf
[33] Ibid.
[34] Ibid.
[35] Based on averages for 2014-2015. Numbers from California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed July 28, 2016.
[36] Ibid.
[37] Ibid.
[38] Ibid.
[39] Email from Andrew DiLuccia, Public Information Officer for the California State Water Resources Control Board, containing quote from Cindy Forbes, Deputy Director of the Division of Drinking Water, on August 8, 2016. Telephone interview with Forbes on August 4, 2016.
[40] California State Water Resources Board, template for public notification of Arsenic MCL Exceedance, Link: http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/Notices.shtml
[41] Ibid.
[42] Example of Consumer Confidence Report for a California system can be found on the state website: https://sdwis.waterboards.ca.gov/PDWW/JSP/WaterSystemDetail.jsp?tinwsys_is_number=370&tinwsys_st_code=CA&wsnumber=CA1000071#
[43] Carolina L. Balazs and Isha Ray, "The Drinking Water Disparities Framework: On the Origins and Persistence of Inequities in Exposure," American Journal of Public Health, April 2014, Vol 104, No. 4. Link: http://www.ncbi.nlm.nih.gov/pubmed/24524500.
[44] Ibid.
[45] Ibid.
[46] Ibid.
[47] 40 CFR 142.20(a)(2)
[48] Wasserman et al. (2014), A Cross-Sectional Study of Well Water Arsenic and Child IQ in Maine Schoolchildren, Environ Health 13:23-32.
[49] U.S. EPA public notification template on EPA website: https://www.epa.gov/dwreginfo/public-notification-templates-community-and-non-transient-non-community-water-systems
[50] Telephone interview on August 25, 2016 with Philip Dutton, engineer for Fresno County.
[51] California State Water Resources Control Board website, http://www.waterboards.ca.gov/drinking_water/certlic/device/watertreatmentdevices.shtml
[52] KFSN-TV, ABC-30 in Fresno, report "Kettleman City Residents Get Answers to Questions about Construction of Water Treatment Plant," August 31, 2016. Link: http://abc30.com/society/kettleman-city-residents-get-answers-to-questions-about-construction-of-water-treatment-plant/1493726/
[53] Ibid.

[54] Telephone interview on August 26, 2016, with Cheryl Sandoval, Supervising Environmental Health Specialist and Manager of Monterey County's drinking water program.
[55] Corral de Tierra Water Company 2013 Consumer Confidence Report, dated July 11, 2014.
[56] Ibid.
[57] Telephone interview on August 26, 2016, with Randy Hardenbrook, Director of the Quail Valley Water District.
[58] Ibid.
[59] Telephone interview on August 25, 2016, with Robert Johnson, President of the Shaver Lake Point 2 Mutual Water Company.
[60] Ibid.
[61] Numbers from California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed July 28, 2016.
[62] Telephone interview with Connie R. Clendenan, CEO of the Valley Teen Ranch nonprofit organization, on August 1, 2016.
[63] Numbers from California State Water Control Resources Board online database, "Drinking Water Watch," https://sdwis.waterboards.ca.gov/PDWW/ Records accessed July 28, 2016
[64] Email from Whitney Meyer, Principal of the Washington School in Salinas, California, on August 1, 2016.
[65] Email from Robert Shemwell, Assistant Superintendent of Business Services of the Yuba City Unified School District, containing quote from Tom Butcher,Director of Maintenance and Facilities, on August 12, 2016.
[66] Email on August 24, 2016, from Liliana Stransky of the Kings County Department of Public Health.
[67] Email from Superintendent Charlotte Hines of the Island Union School in Lemoore, California, August 4, 2016.
[68] Email from Kenneth Drylie, Public Affairs Specialist at Fort Irwin, containing quotes from Muhammad A. Bari, Director Public Works at the forst, on August 11, 2016.
[69] Email from Kylie Barnett, Director Public Relations at Delicato Family Vineyards, August 10, 2016.

ENVIRONMENTAL INTEGRITY PROJECT

1000 Vermont Avenue, NW
Suite 1100
Washington, DC 20005
202-296-8800
www.environmentalintegrity.org

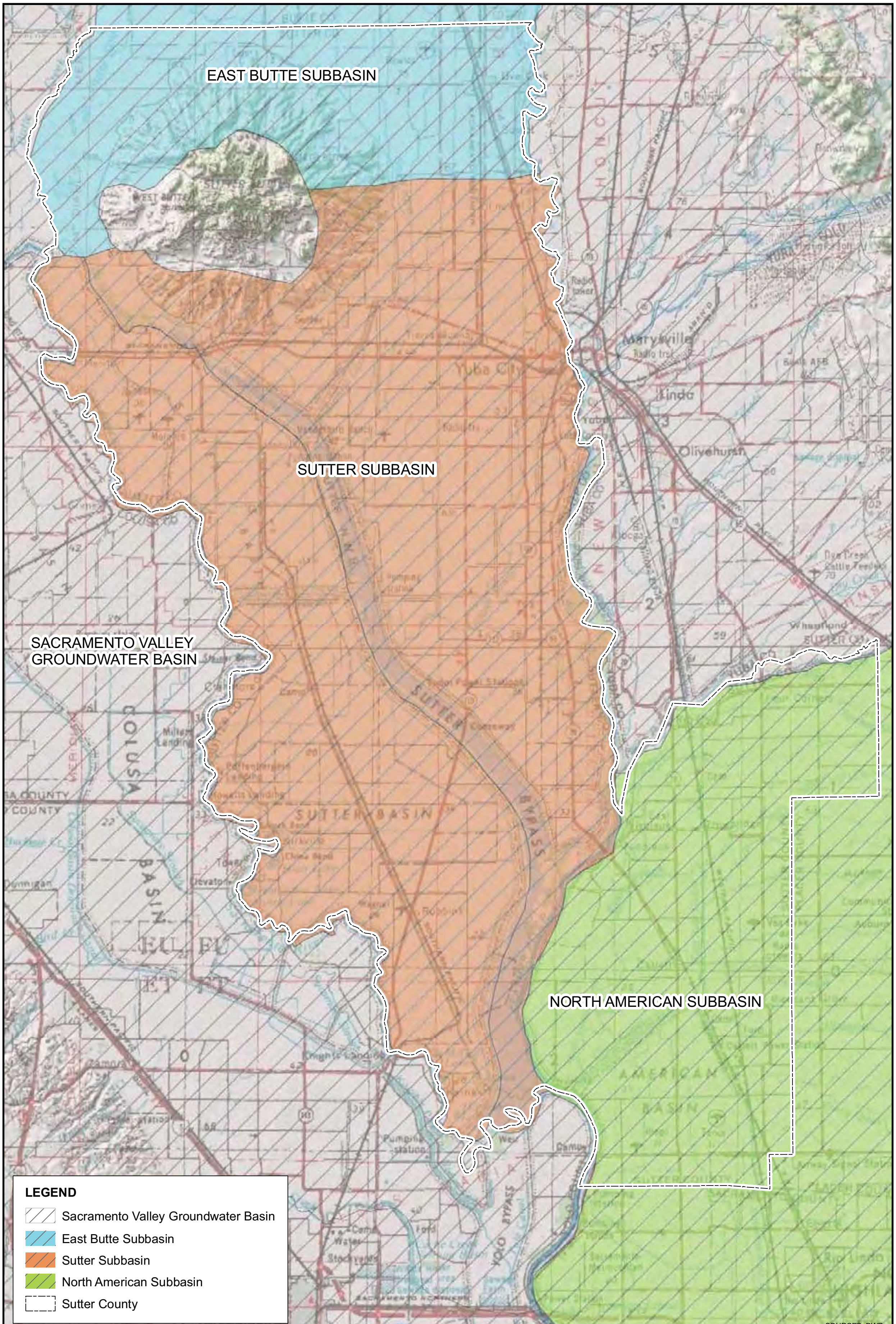


FIGURE 1
GROUNDWATER BASIN AND SUBBASINS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

WOOD RODGERS
DEVELOPING INNOVATIVE DESIGN SOLUTIONS
3301 C Street, Bldg. 100-B Tel: 916.341.7760
Sacramento, CA 95816 Fax: 916.341.7767

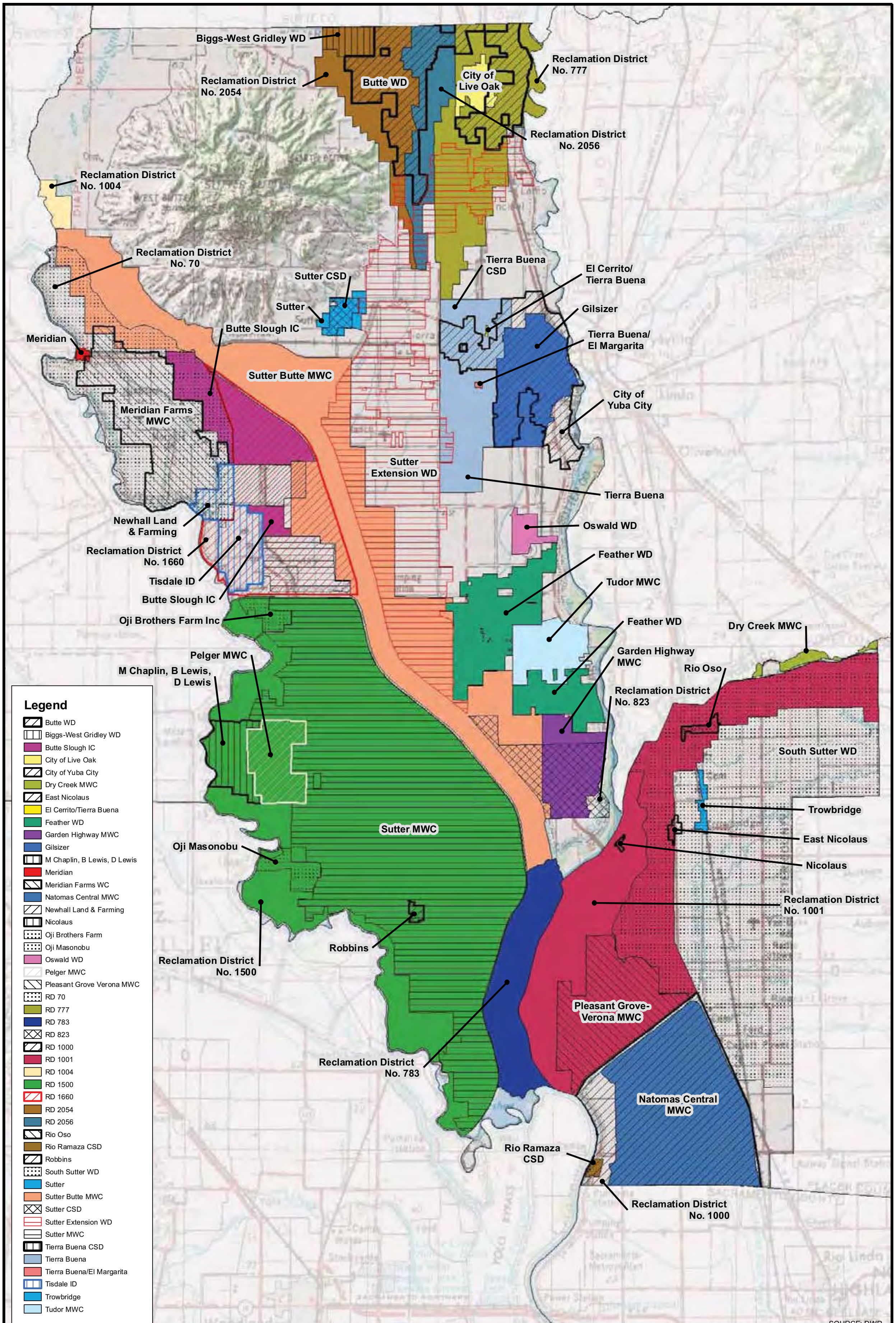


FIGURE 2
WATER DISTRICTS, PURVEYORS, AND WATER COMPANIES

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
MILES

WOOD RODGERS
DEVELOPING INNOVATIVE DESIGN SOLUTIONS
3301 C Street, Bldg. 100-B Tel: 916.341.7760
Sacramento, CA 95816 Fax: 916.341.7767

J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 2 Water_District_Poster.mxd 2/7/2012 12:39:44 PM bdemucha

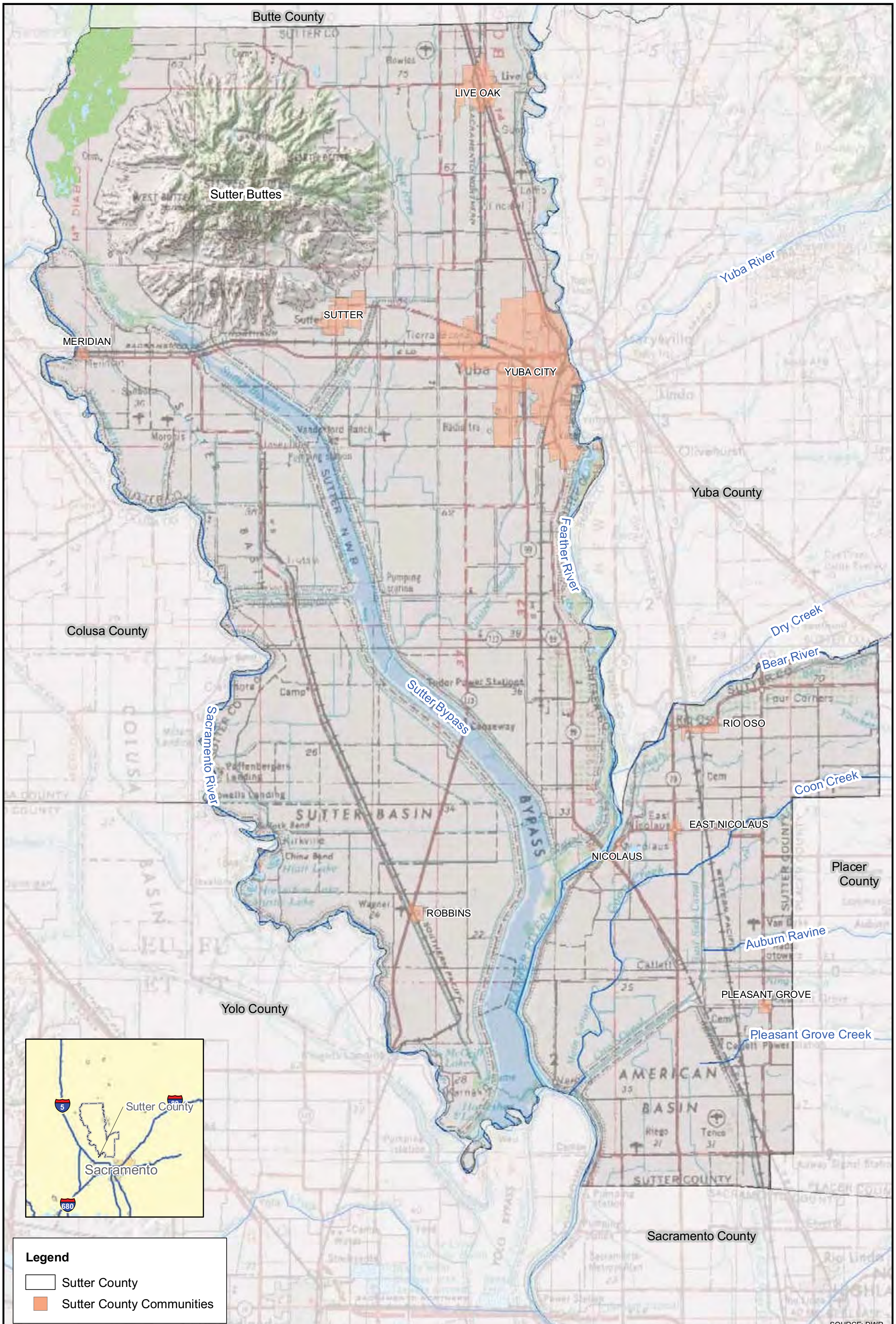


FIGURE 5
PHYSICAL FEATURES
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
MILES

WOOD RODGERS
DEVELOPING INNOVATIVE DESIGN SOLUTIONS
3301 C Street, Bldg. 100-B Sacramento, CA 95816
Tel: 916.341.7760 Fax: 916.341.7767

J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 5 Sutter County Physical Features.mxd 2/7/2012 12:47:54 PM bdemucha

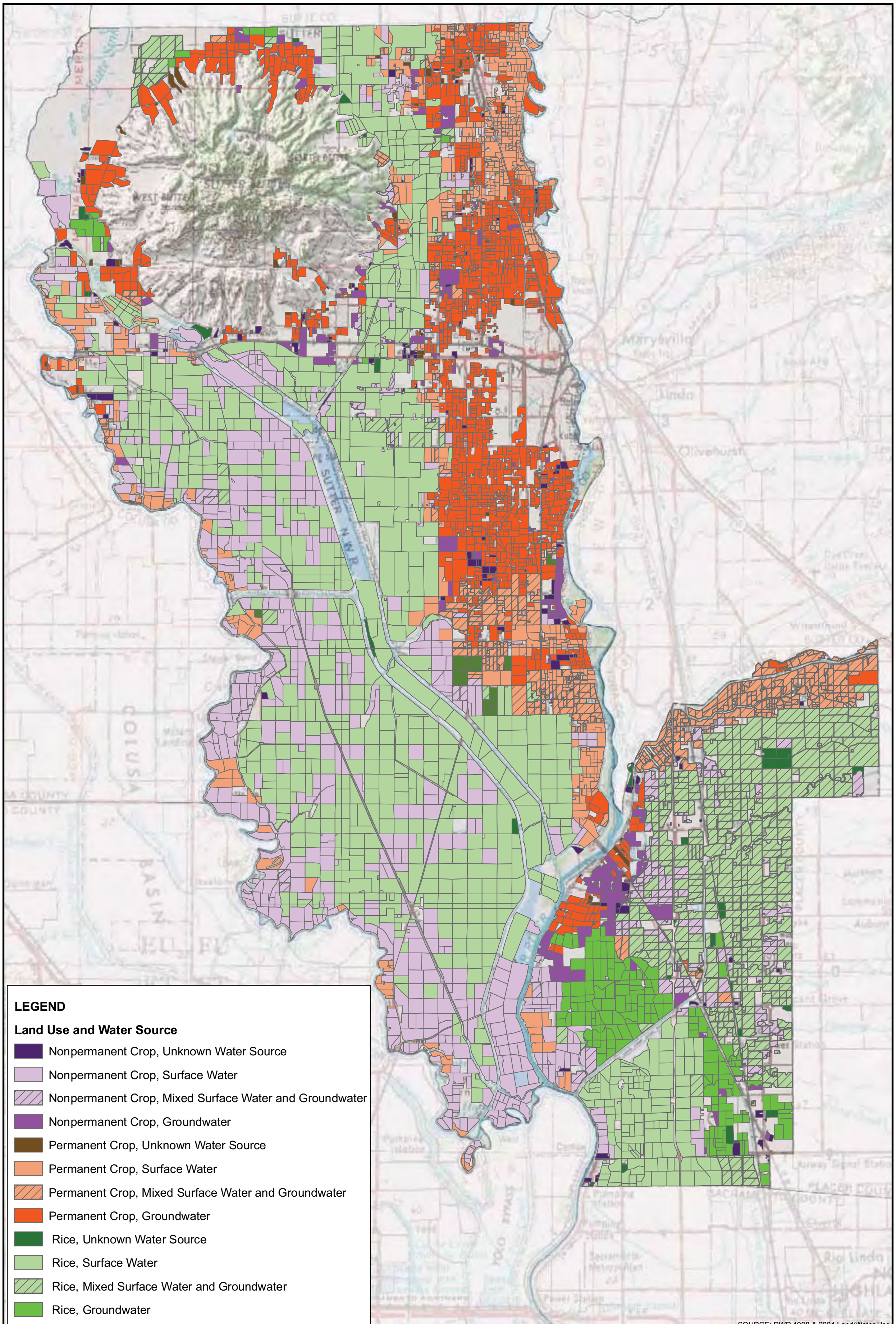


FIGURE 6
WATER SOURCES FOR IRRIGATED CROPS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
Miles

WOOD RODGERS
DEVELOPING INNOVATIVE DESIGN SOLUTIONS
3301 C Street, Bldg. 100-B Tel: 916.341.7760
Sacramento, CA 95816 Fax: 916.341.7767

J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 6 Water_Source_IRR_Crops_.mxd 2/7/2012 12:52:19 PM bdemucha

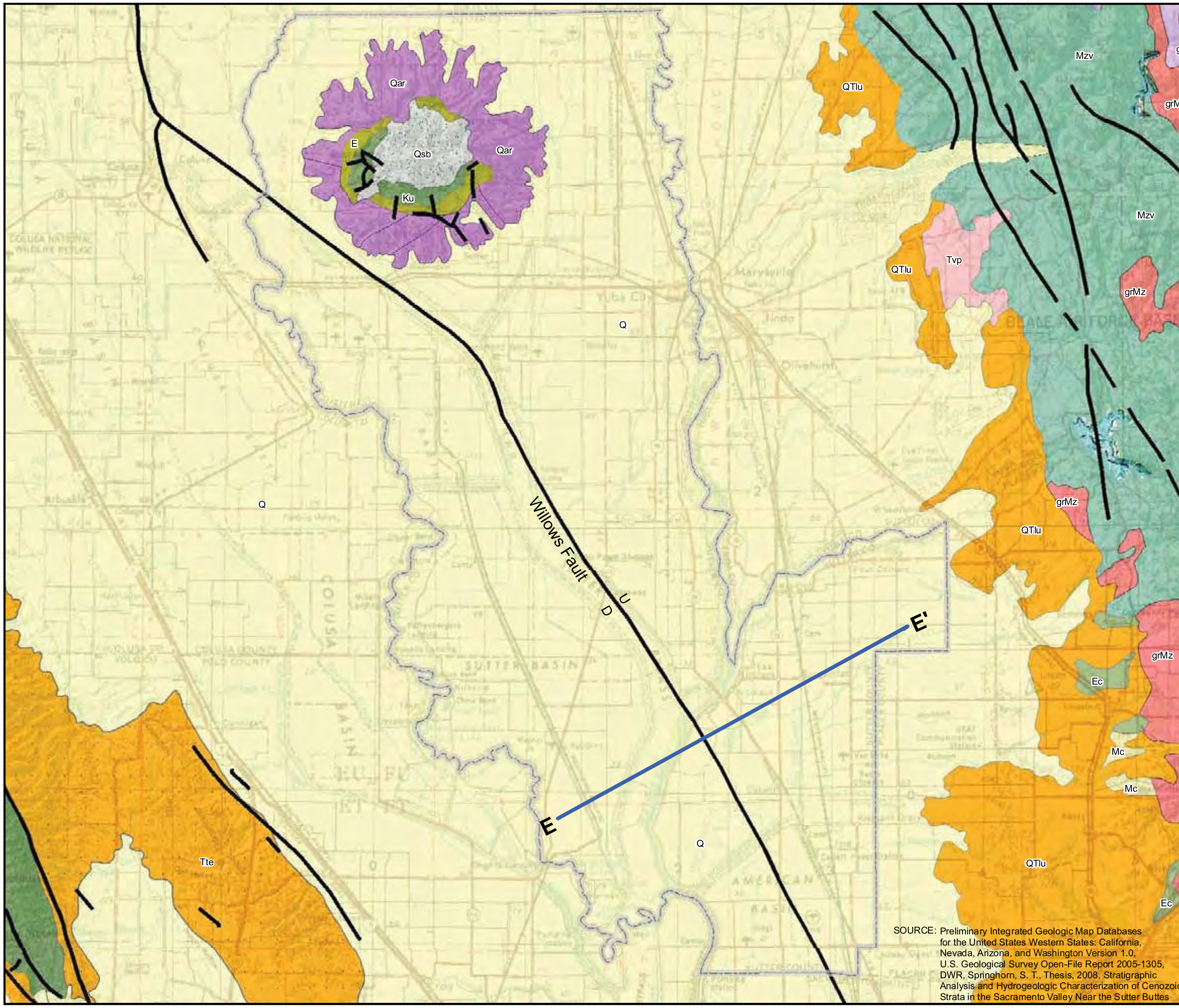


FIGURE 7
SIMPLIFIED SURFACE GEOLOGY AND FAULTS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 2 4
MILES

LEGEND

- Q - Recent Deposits
  - Qb - Basin Deposits
  - Qm - Modesto Formation
  - Qr - Riverbank Formation
- Qsb - Sutter Buttes Igneous Rocks
- Qar - Sutter Buttes Andesitic Rampart
- QTlu - Laguna Formation
- Tte - Tehama Formation
- Tvp - Andesite, Rhyolite
- Mc - Sandstone, Conglomerate
- Ec - Conglomerate, Sandstone
- E - Mudstone, Sandstone
- Ku - Sandstone, Mudstone
- J - Mudstone, Sandstone, & Slate
- um - Serpentinite
- Mzv - Volcanic, Metavolcanic
- gb - Gabbro, Diorite
- grMz - Granodiorite
- Fault
- Fault Displacement - U, upthrown side; D, downthrown side
- Counties
- Simplified Conceptual Geologic Cross Section Line (See Figure 8)

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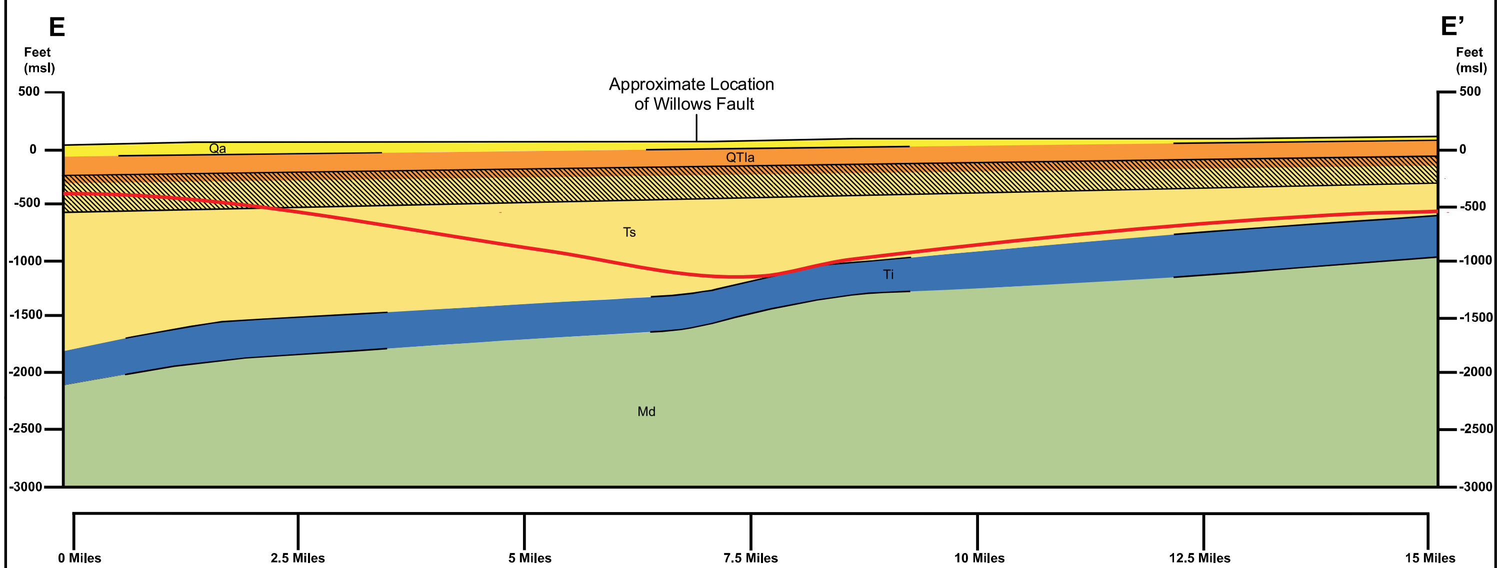
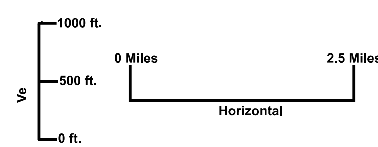
FIGURE 8
SIMPLIFIED CONCEPTUAL GEOLOGIC CROSS SECTION
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012



Explanation

- Qa — Alluvial Deposits
- QTla — Laguna Formation
- Laguna and Sutter Formation Transition (approximate depth)
- Ts — Sutter Formation (map unit, Williams and Curtis, 1977; Helley and Harwood, 1985)
  - Tt — Tuscan Formation (map unit, Helley and Harwood, 1985)
  - Tm — Mehrten Formation (map unit, Helley and Harwood, 1985)
- Ti — Ione Formation (map unit, Helley and Harwood, 1985)
- Md — Marine Deposits
- Inferred Geologic Contact
- Approximate Base of Fresh Water. Line represent depths at which Specific Conductance levels exceed approximately 3,000 umhos/cm

Cross Section Scale



SOURCES: DOGGR; DWR; Springhorn, S. T., Thesis, 2008, Stratigraphic Analysis and Hydrogeologic Characterization of Cenozoic Strata in the Sacramento Valley Near the Sutter Buttes; Berkstresser, C.F. Jr. 1973. Base of Fresh Ground-Water -- Approximately 3,000 micromhos in the Sacramento Valley and Sacramento-San Joaquin Delta, California. U.S. Geological Survey Water-Resource Inv. 40-73; Helley, E. J. and Harwood, D. S., 1985, Geologic Map of Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California.

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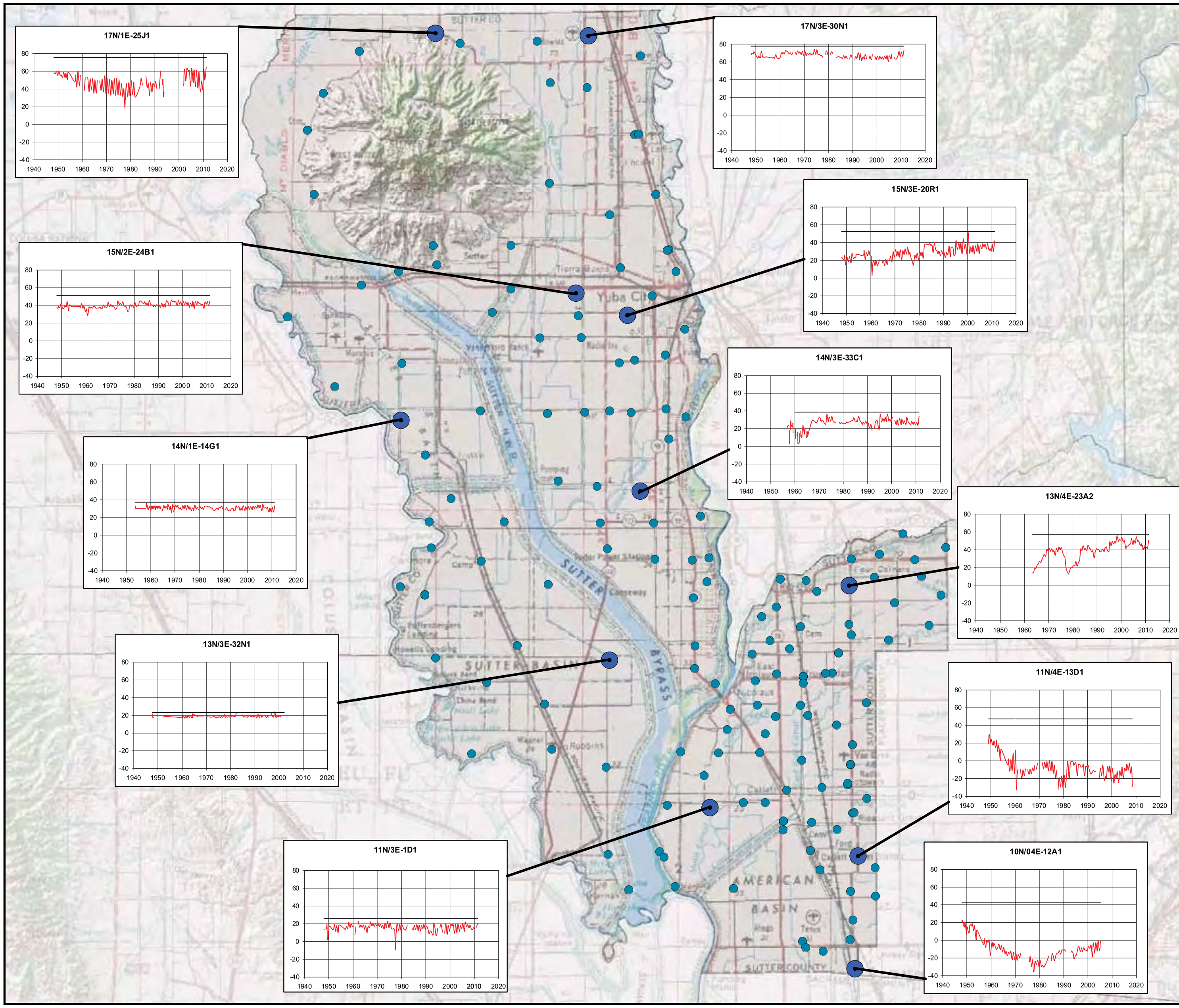


FIGURE 9
HISTORIC GROUNDWATER ELEVATIONS IN SUTTER COUNTY
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

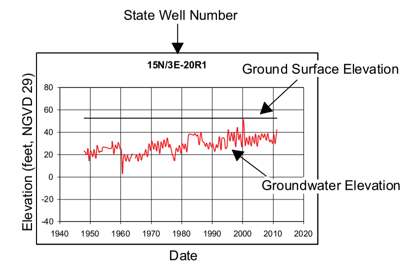
NORTH

0 2 4
MILES

Legend
- Well with Hydrograph Shown
- Well with Water Level Measurement since 2004

Note: This figure represents wells with historic water level and current measurements either submitted to or obtained by the California Department of Water Resources and may not represent current monitoring activities. Groundwater elevations are in feet above mean sea level.

SOURCE: DWR



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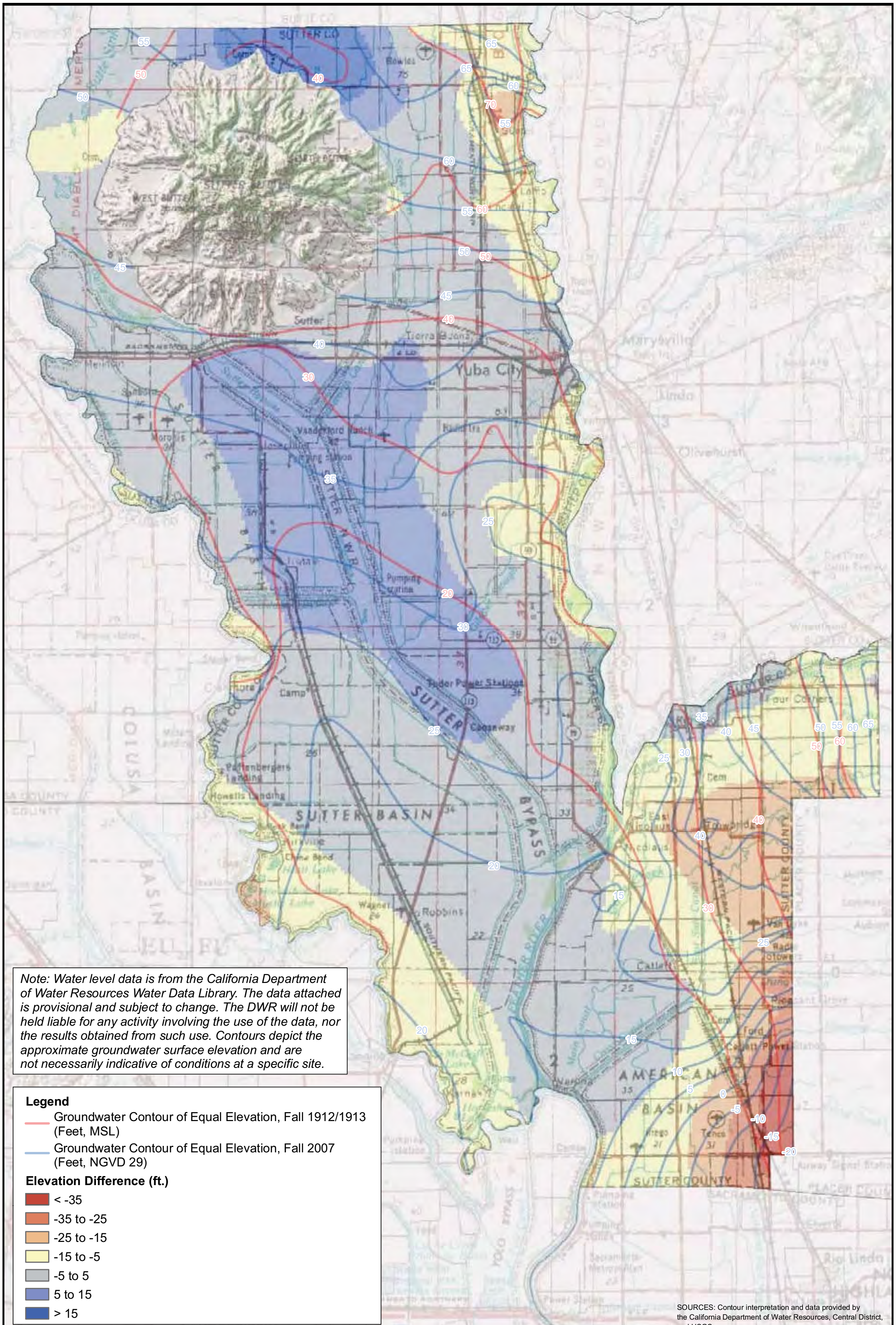

Note: Water level data is from the California Department of Water Resources Water Data Library. The data attached is provisional and subject to change. The DWR will not be held liable for any activity involving the use of the data, nor the results obtained from such use. Contours depict the approximate groundwater surface elevation and are not necessarily indicative of conditions at a specific site.

Legend

- Groundwater Contour of Equal Elevation, Fall 1912/1913 (Feet, MSL)
- Groundwater Contour of Equal Elevation, Fall 2007 (Feet, NGVD 29)

Elevation Difference (ft.)

- < -35
- -35 to -25
- -25 to -15
- -15 to -5
- -5 to 5
- 5 to 15
- > 15

SOURCES: Contour interpretation and data provided by the California Department of Water Resources, Central District, and USGS

FIGURE 10
GROUNDWATER LEVEL CHANGE MAP
FALL 2007 AND FALL 1912/1913
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
MILES

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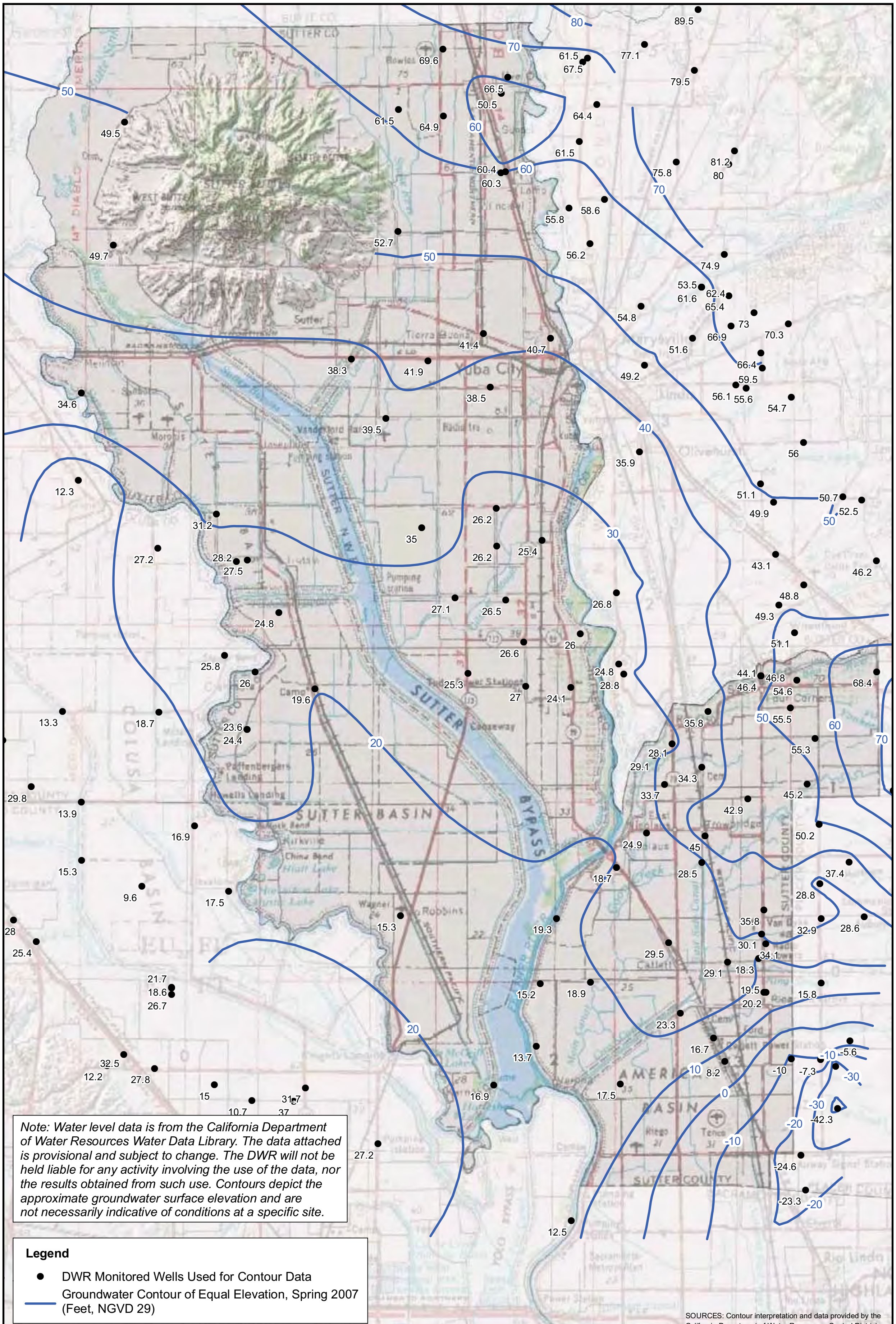

Note: Water level data is from the California Department of Water Resources Water Data Library. The data attached is provisional and subject to change. The DWR will not be held liable for any activity involving the use of the data, nor the results obtained from such use. Contours depict the approximate groundwater surface elevation and are not necessarily indicative of conditions at a specific site.

Legend

- DWR Monitored Wells Used for Contour Data
- Groundwater Contour of Equal Elevation, Spring 2007 (Feet, NGVD 29)

SOURCES: Contour interpretation and data provided by the California Department of Water Resources, Central District

FIGURE 11
GROUNDWATER ELEVATION CONTOUR MAP
SPRING, 2007

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH

0 1.5 3
Miles

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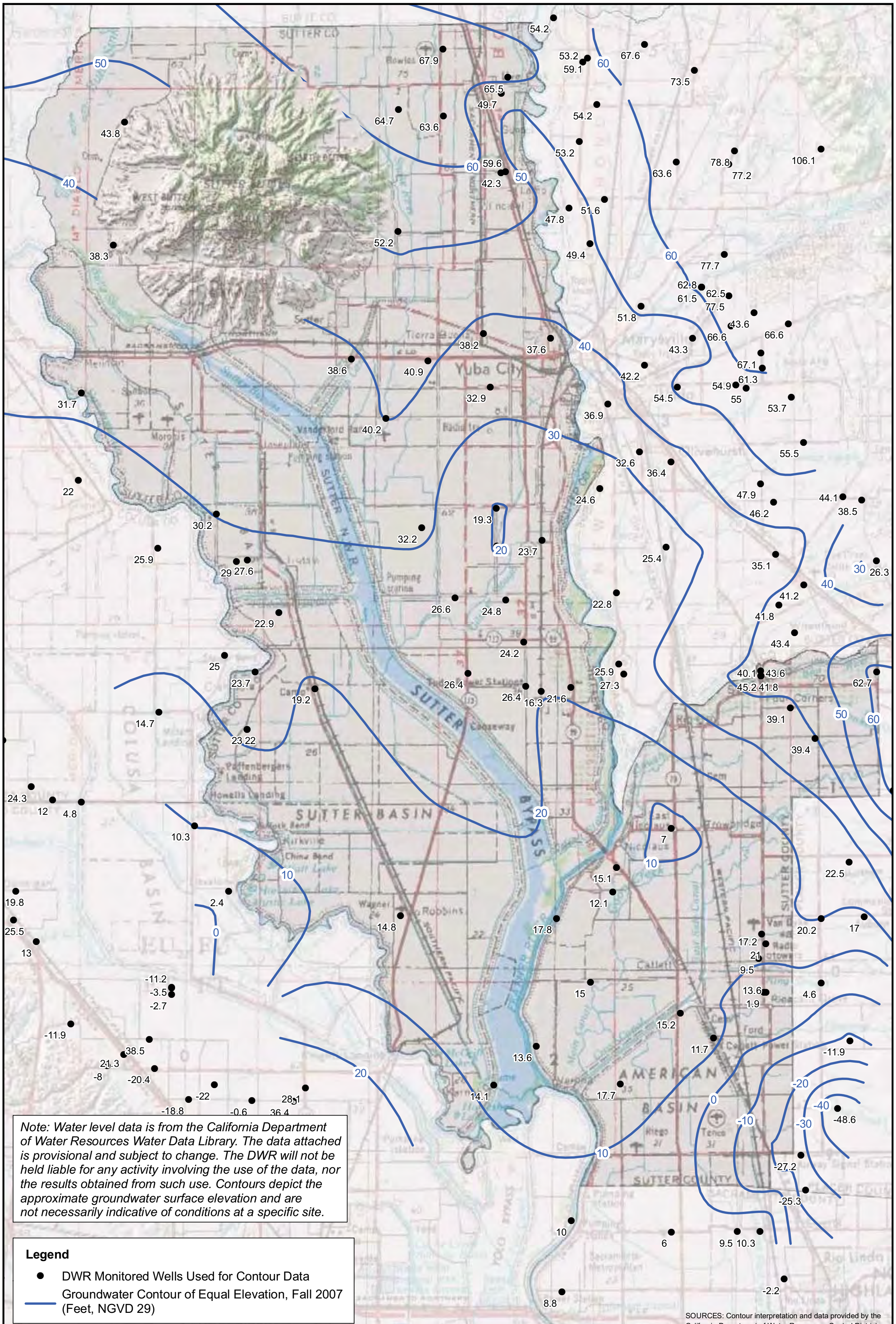
J:\Jobs\8337_SutterCounty\GIS\Tasks\20120201 Final Draft Figure Comments\Figure 11 Groundwater Elevation Contour Map Spring 2007.mxd 2/7/2012 5:55:07 PM bdemucha



Note: Water level data is from the California Department of Water Resources Water Data Library. The data attached is provisional and subject to change. The DWR will not be held liable for any activity involving the use of the data, nor the results obtained from such use. Contours depict the approximate groundwater surface elevation and are not necessarily indicative of conditions at a specific site.

Legend

- DWR Monitored Wells Used for Contour Data
- Groundwater Contour of Equal Elevation, Fall 2007 (Feet, NGVD 29)

FIGURE 12
GROUNDWATER ELEVATION CONTOUR MAP
FALL, 2007

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
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NORTH

0 1.5 3
Miles

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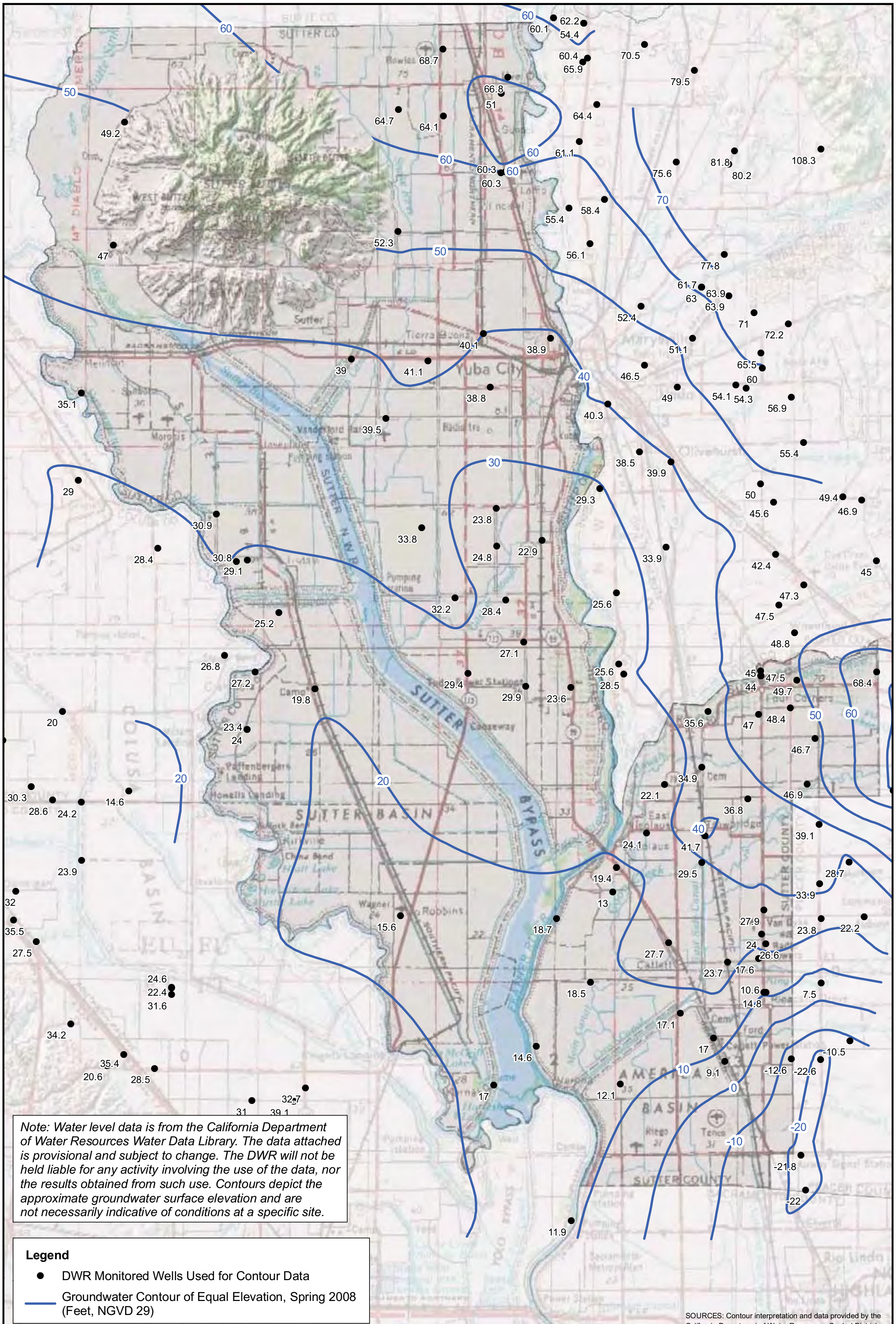
J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 12 Groundwater Elevation Contour Map Fall 2007.mxd 2/7/2012 6:07:59 PM bdemucha



Note: Water level data is from the California Department of Water Resources Water Data Library. The data attached is provisional and subject to change. The DWR will not be held liable for any activity involving the use of the data, nor the results obtained from such use. Contours depict the approximate groundwater surface elevation and are not necessarily indicative of conditions at a specific site.

Legend

- DWR Monitored Wells Used for Contour Data
- Groundwater Contour of Equal Elevation, Spring 2008 (Feet, NGVD 29)

SOURCES: Contour interpretation and data provided by the California Department of Water Resources, Central District

FIGURE 13

GROUNDWATER ELEVATION CONTOUR MAP
SPRING, 2008

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NORTH

0 1.5 3
Miles

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J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 13 Groundwater Elevation Contour Map Spring 2008.mxd 2/7/2012 6:20:59 PM bdemucha

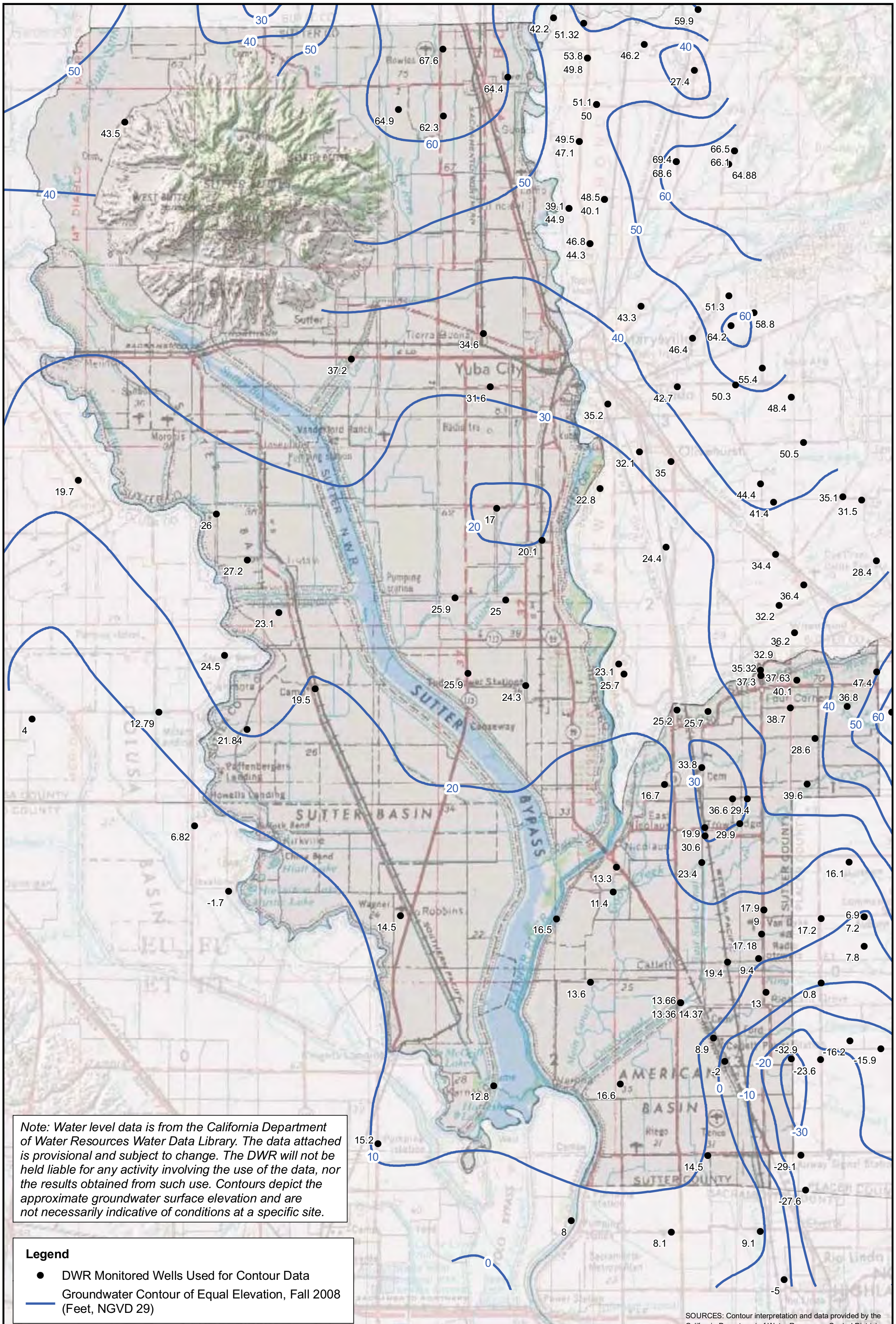

FIGURE 14

GROUNDWATER ELEVATION CONTOUR MAP FALL, 2008

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NORTH

0 1.5 3
Miles

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J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 14 Groundwater Elevation Contour Map Fall 2008.mxd 2/8/2012 9:20:28 AM bdemucha

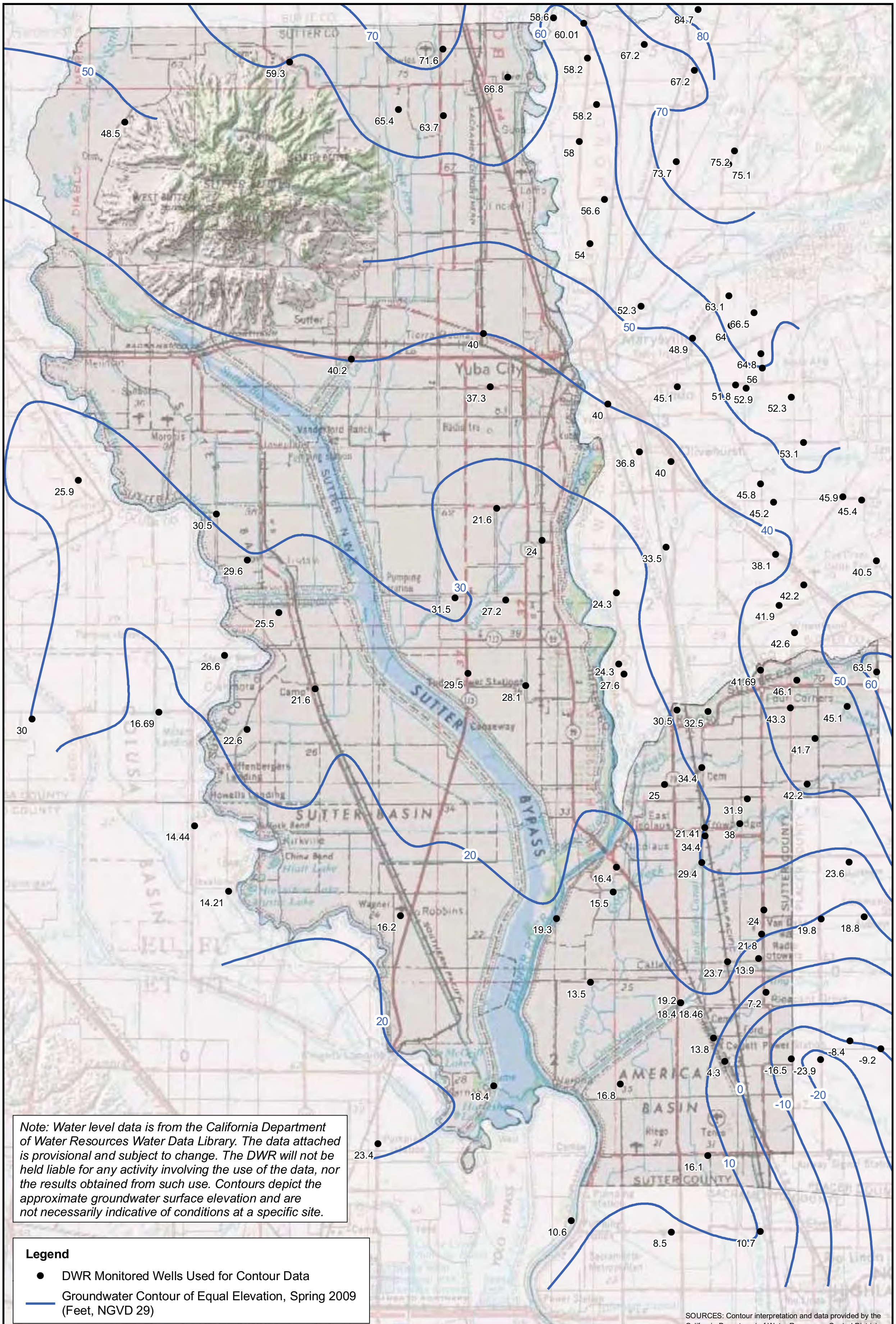

FIGURE 15
GROUNDWATER ELEVATION CONTOUR MAP
SPRING, 2009

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
Miles

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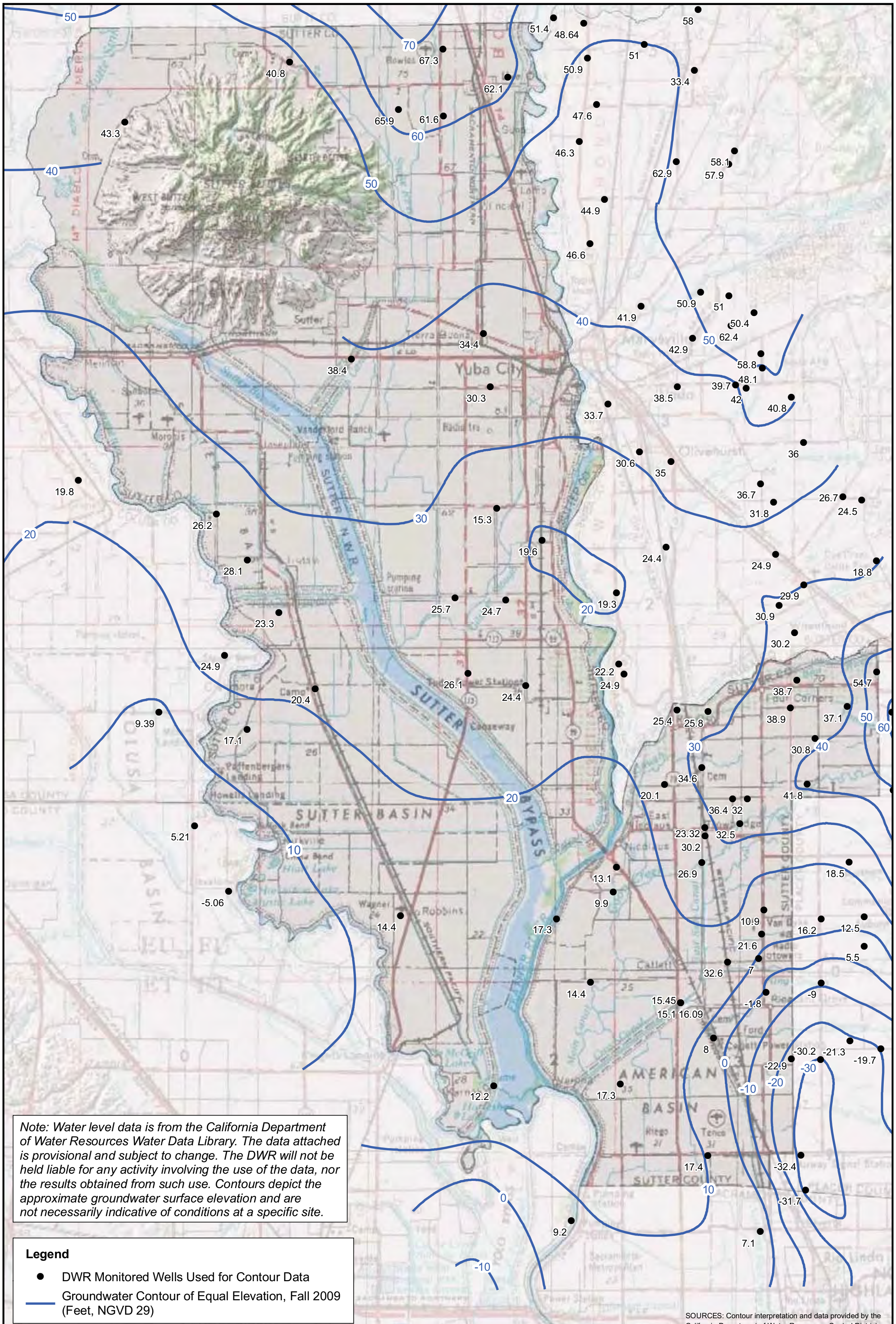

Note: *Water level data is from the California Department of Water Resources Water Data Library. The data attached is provisional and subject to change. The DWR will not be held liable for any activity involving the use of the data, nor the results obtained from such use. Contours depict the approximate groundwater surface elevation and are not necessarily indicative of conditions at a specific site.*

Legend

- ● DWR Monitored Wells Used for Contour Data
- — Groundwater Contour of Equal Elevation, Fall 2009 (Feet, NGVD 29)

SOURCES: Contour interpretation and data provided by the California Department of Water Resources, Central District

FIGURE 16
GROUNDWATER ELEVATION CONTOUR MAP
FALL, 2009

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
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NORTH

0 1.5 3
Miles

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J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 16 Groundwater Elevation Contour Map Fall 2009.mxd 2/8/2012 9:44:53 AM bdemucha

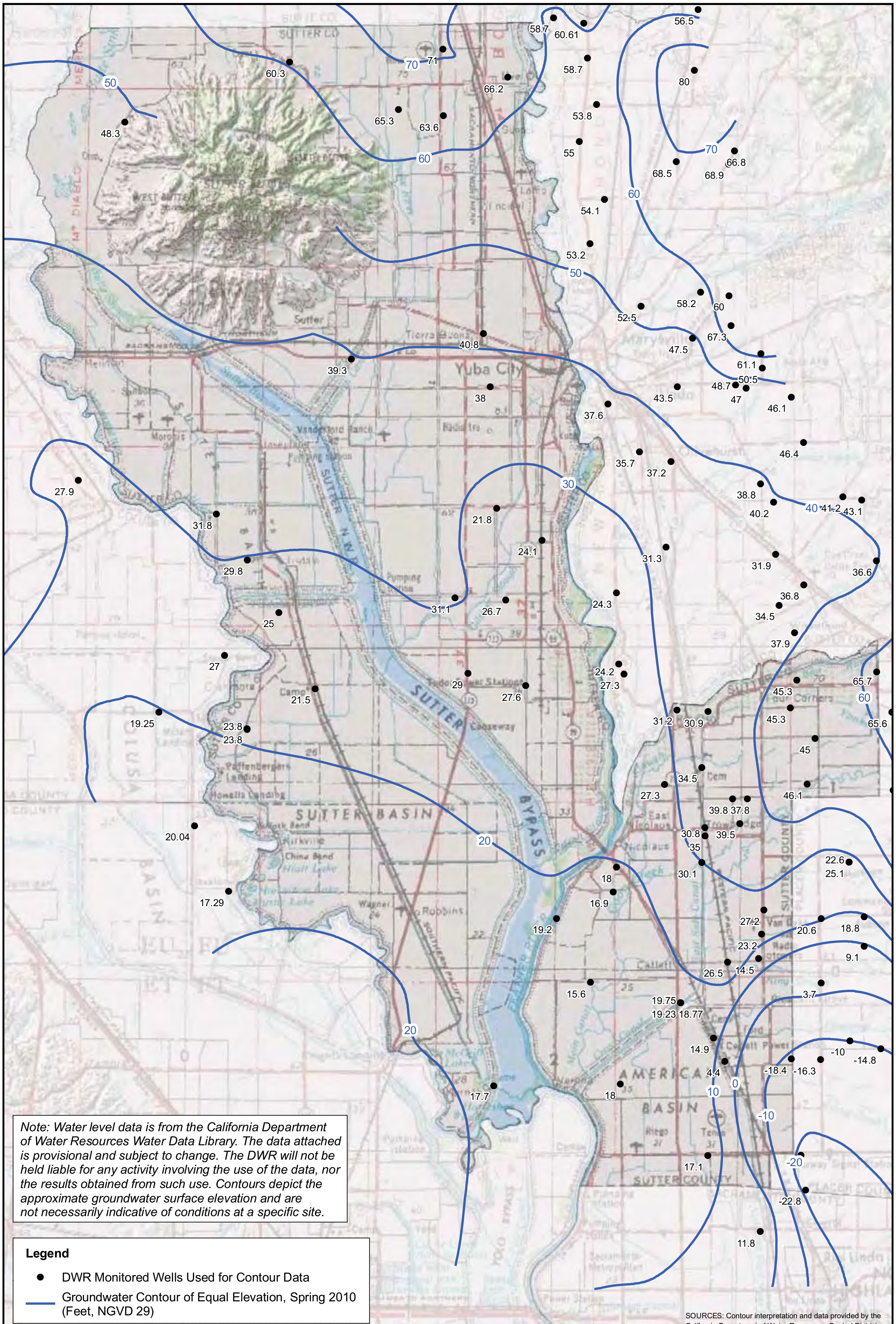

FIGURE 17
GROUNDWATER ELEVATION CONTOUR MAP
SPRING, 2010

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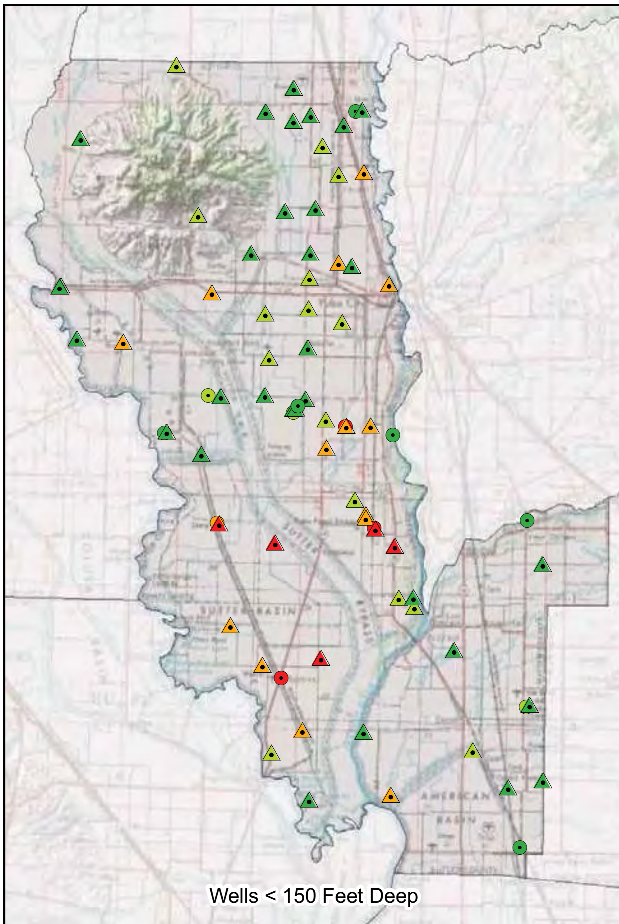

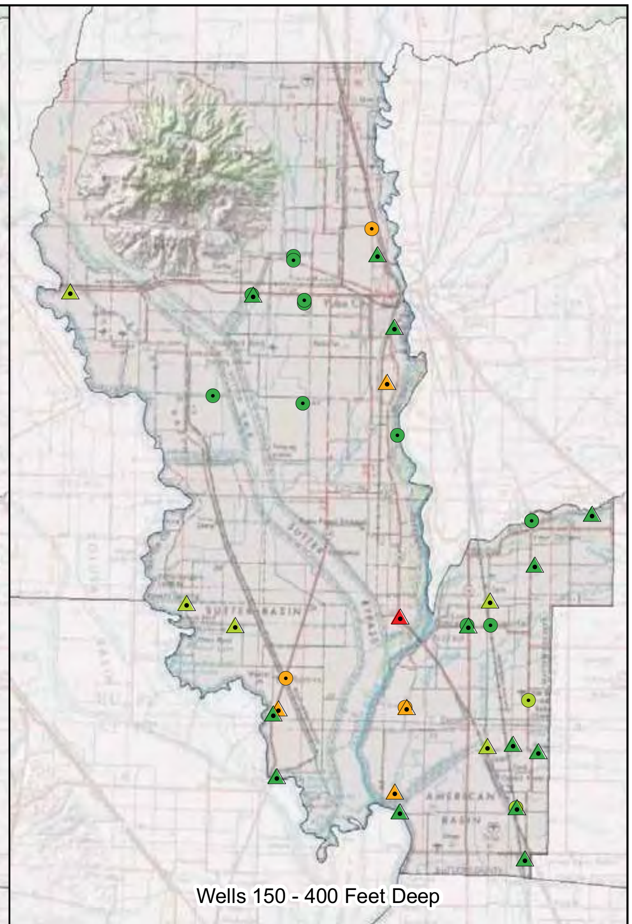

EC in DWR Wells (µmhos/cm)

- < 600
- 600 - 900
- 900 - 1600
- > 1600

EC in USGS Wells (µmhos/cm)

- < 600
- 600 - 900
- 900 - 1600
- > 1600

Note:
"EC" is an abbreviation for specific conductance, which is related to the salt content of a water sample.

For public drinking water systems, the secondary (aesthetic) maximum contaminant levels for EC are 900 micromhos/centimeter (µmhos/cm) (recommended), 1600 µmhos/cm (upper), and 2200 µmhos/cm (short-term).

For irrigation, crop yields decrease above a threshold EC value, which is crop-dependent. Crop yield potential decreases above these threshold levels:

Almonds - 1000 µmhos/cm
Beans - 700 µmhos/cm
Rice - 2000 µmhos/cm
Squash - 2100-3100 µmhos/cm
Tomatoes - 1700 µmhos/cm
Wheat - 4000 µmhos/cm

SOURCES: USGS, DWR, SEWD, DHS, FAO, EPA

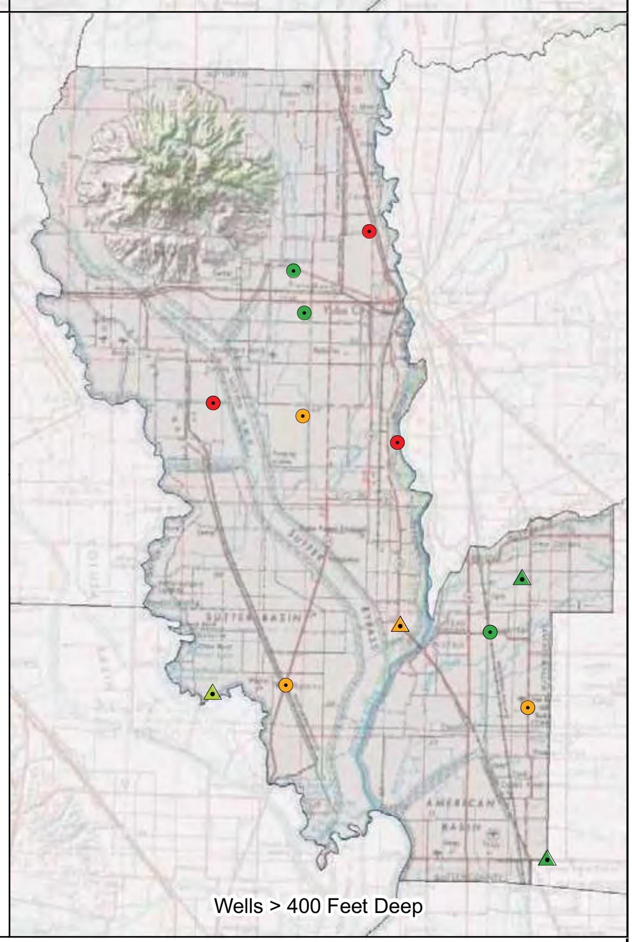

FIGURE 18
SPECIFIC CONDUCTANCE BY WELL DEPTH
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 3 6
Miles

SUTTER COUNTY CALIFORNIA

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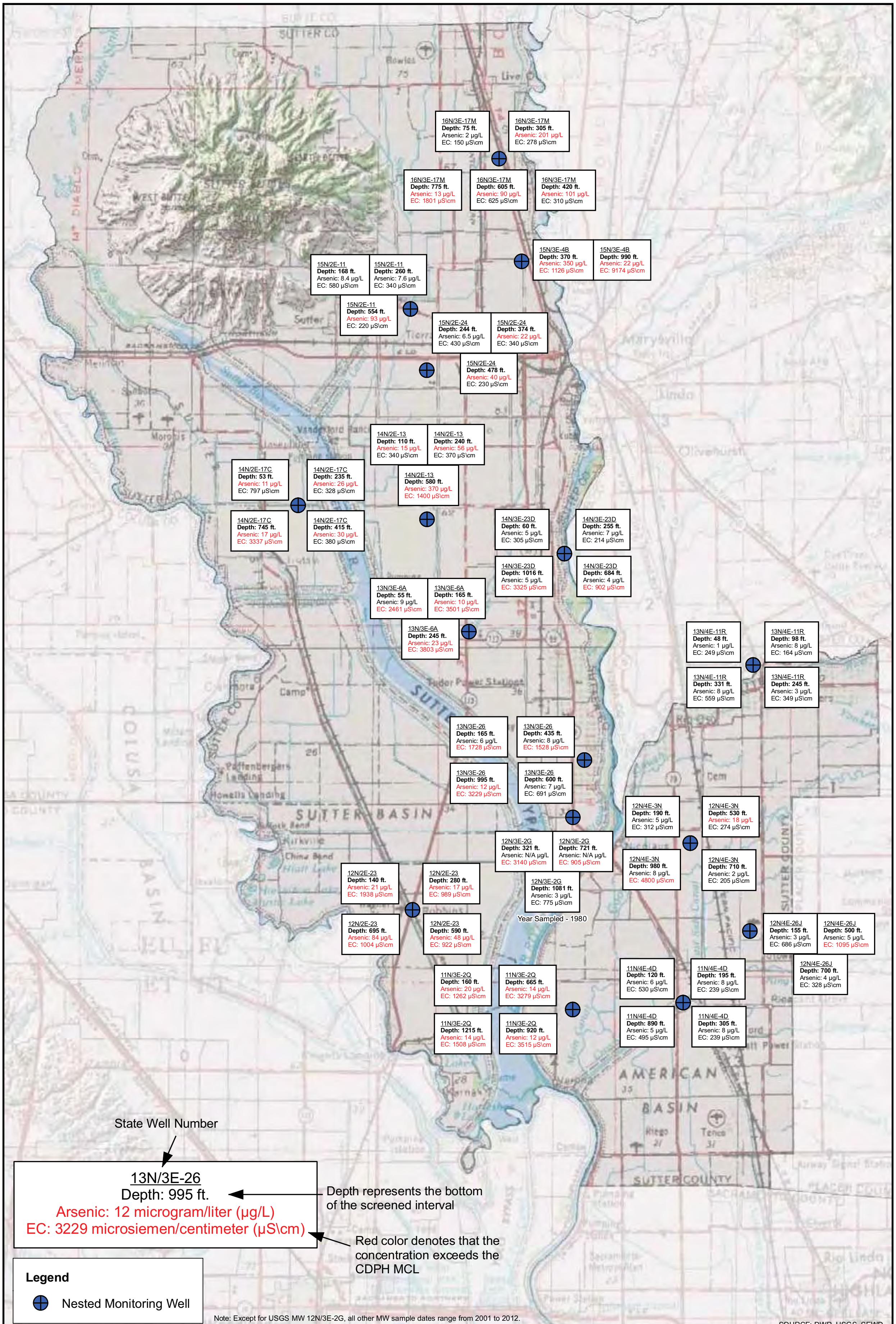

FIGURE 19
DEPTH SPECIFIC ARSENIC AND SPECIFIC CONDUCTANCE CONCENTRATIONS

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 1.5 3
MILES

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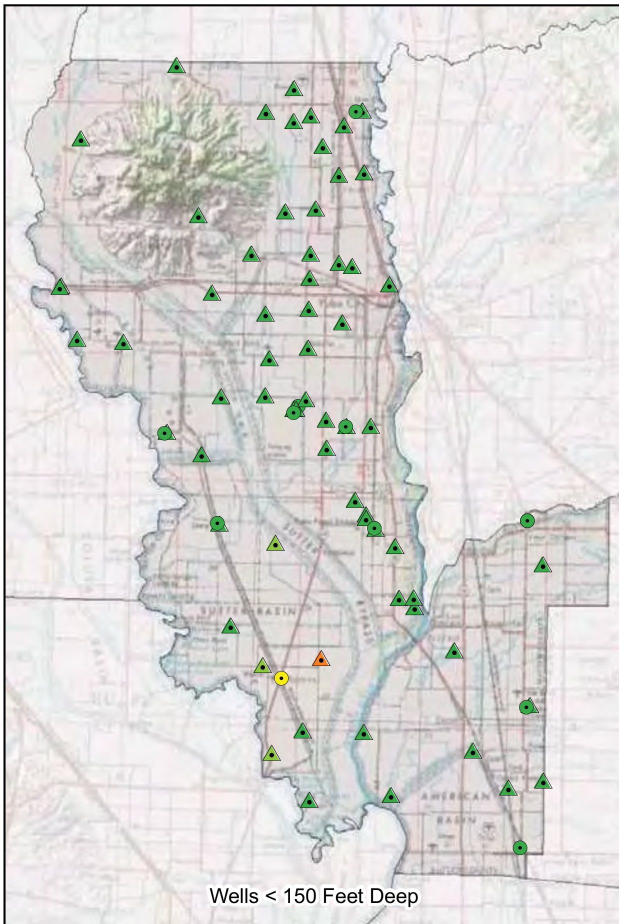
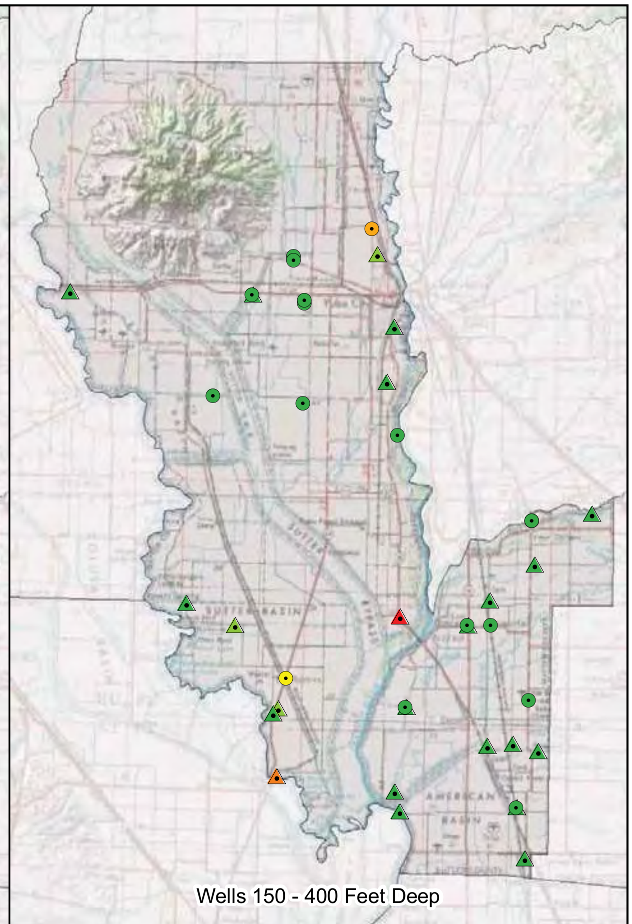
J:\Jobs\8337_SutterCounty\GIS\Tasks\20120201 Final Draft Figure Comments\Figure 19 Depth Specific Arsenic and Specific Conductance.mxd 2/8/2012 11:34:41 AM bdemucha





Boron in DWR Wells (µg/L)

- < 500
- 500 - 750
- 750 - 1000
- 1000 - 2000
- > 2000

Boron in USGS Wells (µg/L)

- < 500
- 500 - 750
- 750 - 1000
- 1000 - 2000
- > 2000

Note:
Boron is naturally occurring and leaches from aquifer materials into groundwater.

For public drinking water systems, there is a notification level for boron of 1000 micrograms/liter (µg/L).

For irrigation, boron is necessary for crop growth but becomes toxic to the point that yields may decrease above these threshold levels:

Beans - 750 - 1000 µg/L
Grapes - 500 - 750 µg/L
Squash - 2000 - 4000 µg/L
Tomatoes - 4000 - 6000 µg/L
Walnuts - 500 - 750 µg/L
Wheat - 750 - 1000 µg/L

Many other trees are vulnerable to boron toxicity above 500 - 750 µg/L.

SOURCES: USGS, DWR, SEWD, DHS, FAO, EPA

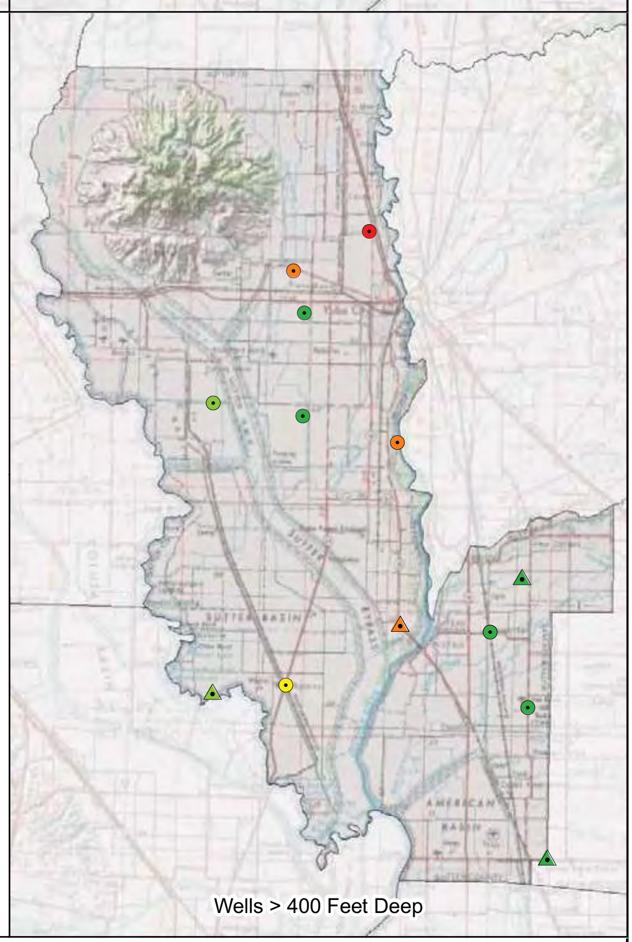


FIGURE 20
BORON BY WELL DEPTHS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 3 6
MILES

SUTTER COUNTY CALIFORNIA

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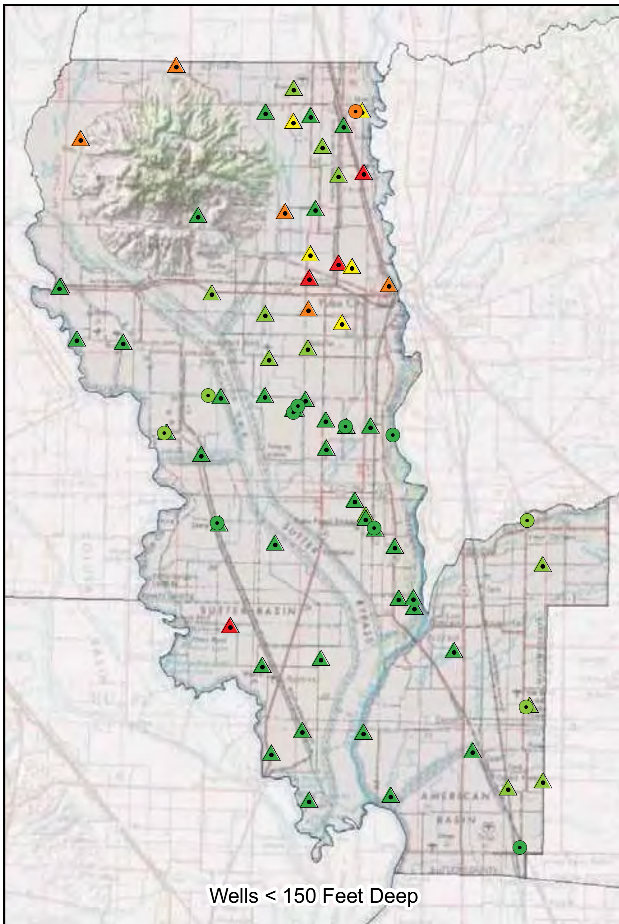

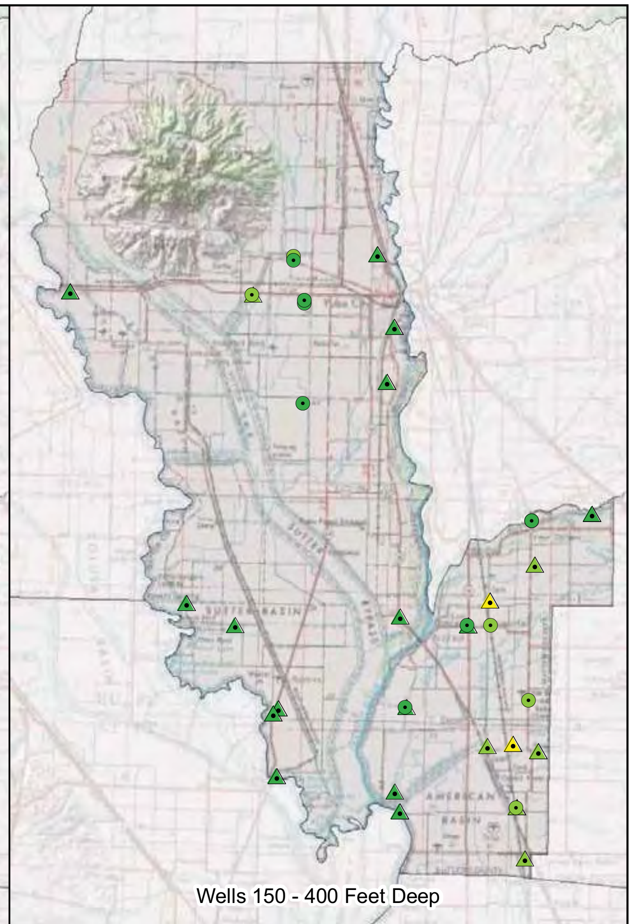

Nitrate in DWR Wells (mg/L)

- < 5
- 5 - 15
- 15 - 30
- 30 - 45
- > 45

Nitrate in USGS Wells (mg/L)

- < 15
- 5 - 15
- 15 - 30
- 30 - 45
- > 45

Note:
Nitrate is generally introduced into groundwater by septic systems, fertilizers, or confined animal operations.

For public drinking water systems, the primary (health-based) maximum contaminant level for nitrate as NO3 is 45 milligrams/liter (mg/L).

At concentrations exceeding the maximum contaminant level, nitrate can interfere with the blood's ability to carry oxygen. This effect can be especially pronounced in infants, where it is known as "blue baby syndrome".

SOURCES: USGS, DWR, SEWD, DHS, FAO, EPA

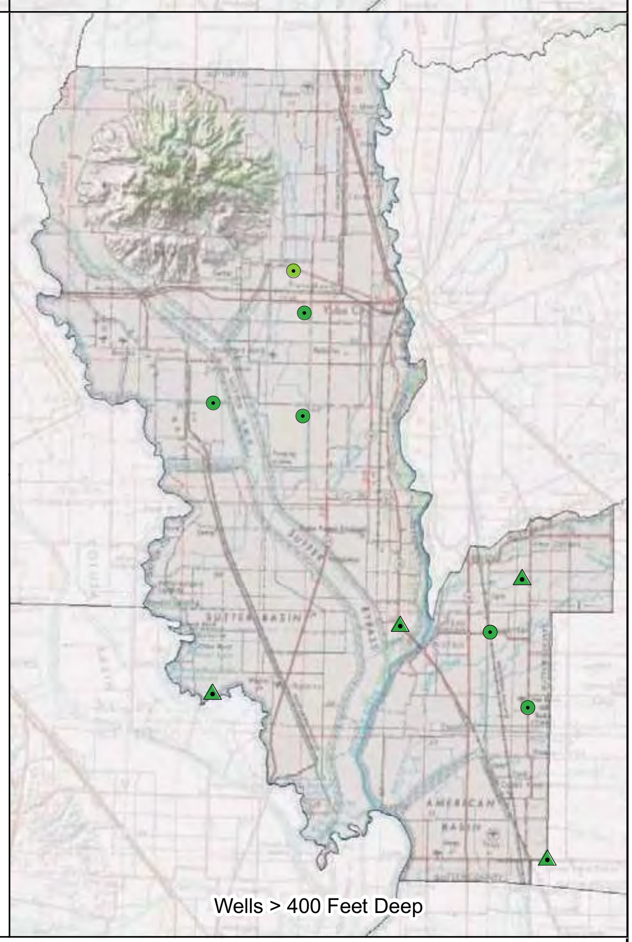

FIGURE 21
NITRATE BY WELL DEPTH
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 3 6
MILES

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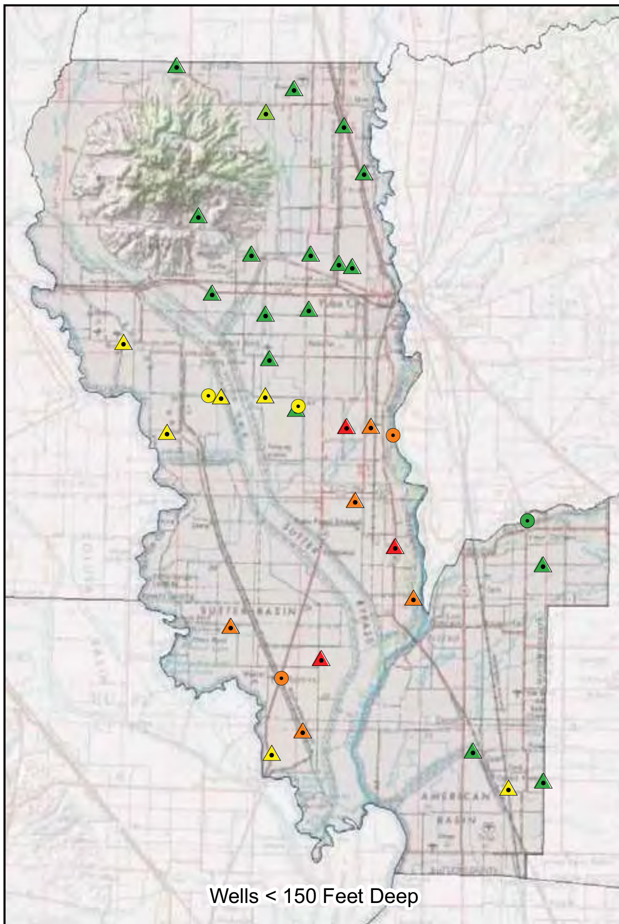

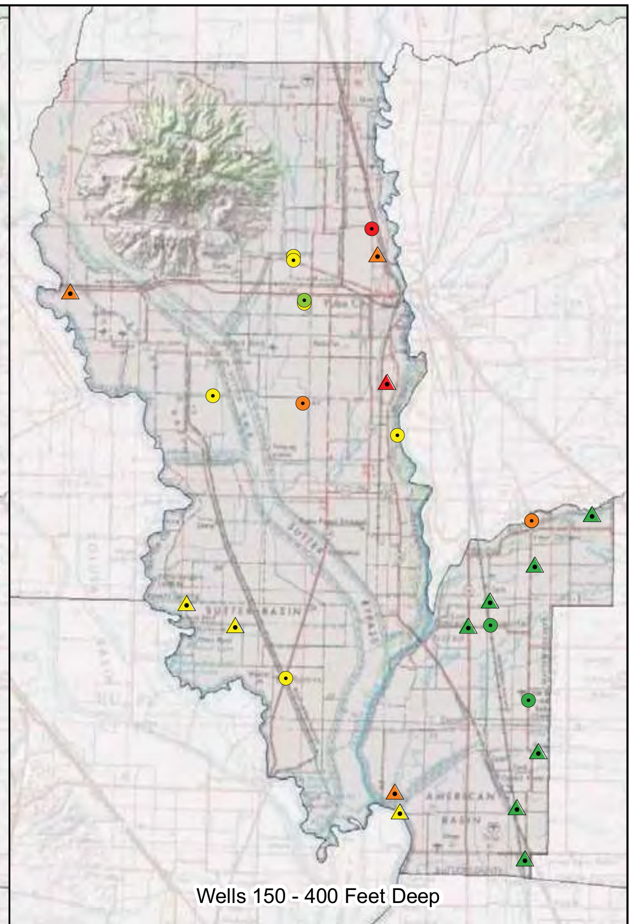

Manganese in DWR Wells (µg/L)

- < 25
- 25 - 50
- 50 - 150
- 150 - 500
- > 500

Manganese in USGS Wells (µg/L)

- < 25
- 25 - 50
- 50 - 150
- 150 - 500
- > 500

Note:
Manganese is naturally occurring and leaches from aquifer materials into groundwater.

For public drinking water systems, the secondary (aesthetic) maximum contaminant level for manganese is 50 micrograms/liter (µg/L). There is also a notification level for manganese of 500 µg/L. Notification levels are health-based advisory levels for chemicals that do not have primary maximum contaminant levels.

Manganese can cause staining of plumbing and fixtures, and can contribute a metallic odor to water. At very high concentrations (above the notification level) manganese may cause neurologic problems.

Analysis for manganese is very sensitive to turbidity of samples - turbid samples will often have artificially high results for manganese.

SOURCES: USGS, DWR, SEWD, DHS, FAO, EPA

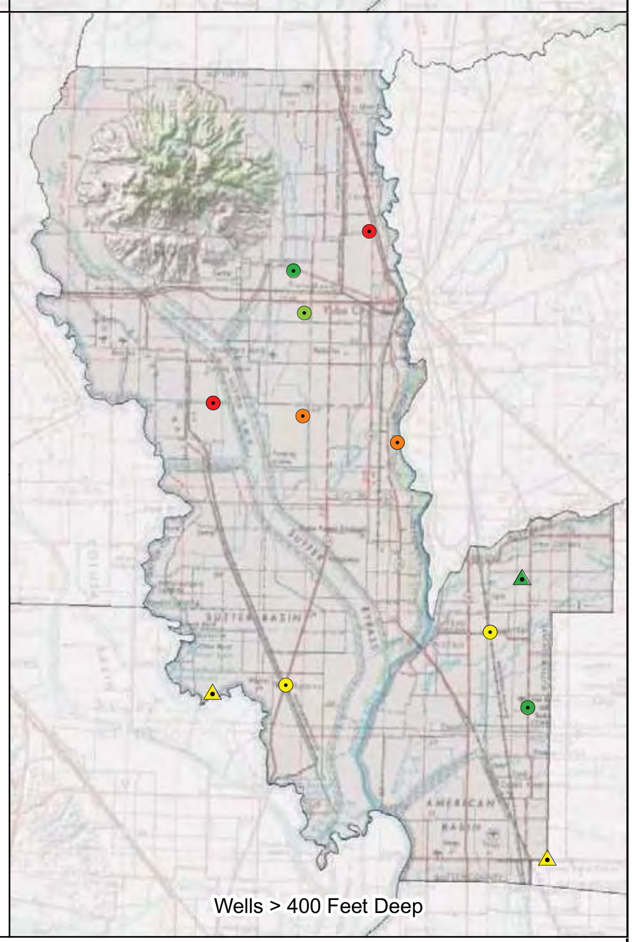

FIGURE 22
MANGANESE BY WELL DEPTHS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 3 6
MILES

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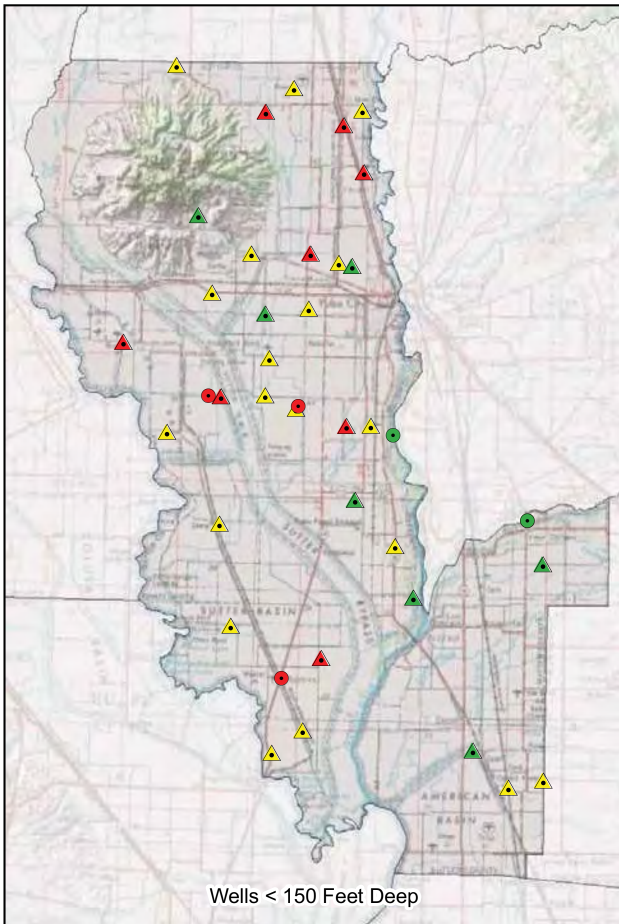
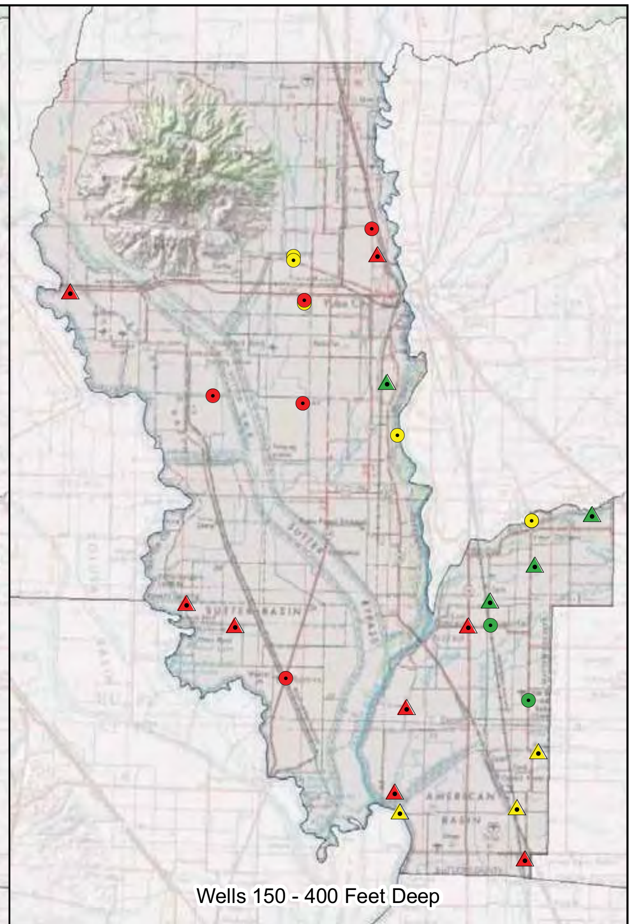
J:\Jobs\8337_SutterCounty\GIS\Tasks\20120201 Final Draft Figure Comments\Figure 22 Manganese_Well Depth.mxd 2/8/2012 3:23:15 PM bdemucha





Arsenic in DWR Wells (µg/L)

- < 5
- 5 - 10
- > 10

Arsenic in USGS Wells (µg/L)

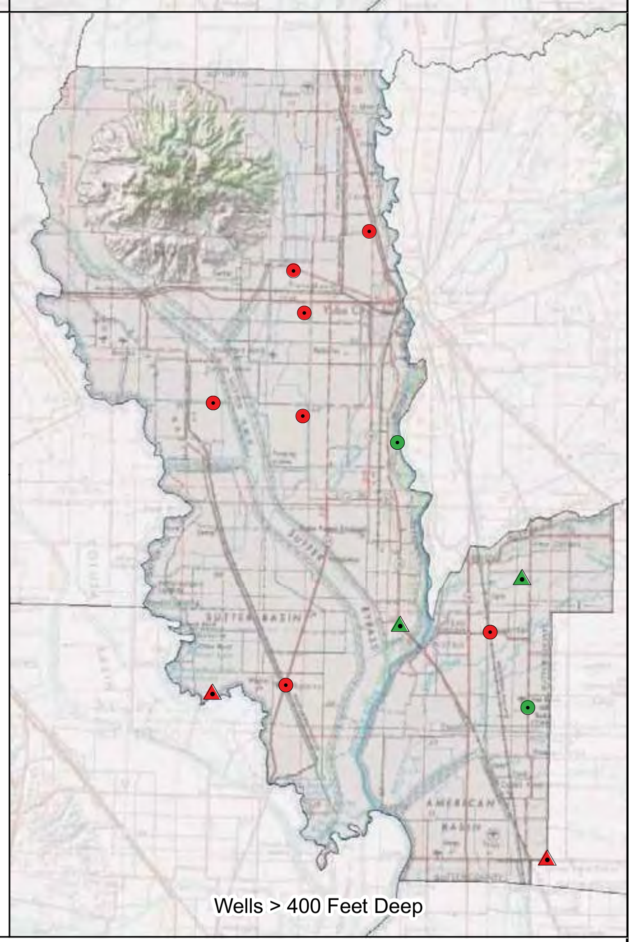
- < 5
- 5 - 10
- > 10

Note:
Arsenic is naturally occurring and leaches from aquifer materials into groundwater.

For public drinking water systems, the primary maximum contaminant level for arsenic is 10 micrograms/liter (µg/L).

Exposure to arsenic can cause both short and long term health effects. Long term exposure to arsenic has been linked to cancer of the bladder, lungs, skin, kidneys, nasal passages, liver and prostate. Short term exposure to high doses of arsenic can cause other adverse health effects.

Analysis for arsenic is very sensitive to turbidity of samples - turbid samples will often have artificially high results for arsenic.



SOURCES: USGS, DWR, SEWD, DHS, FAO, EPA

FIGURE 23
ARSENIC BY WELL DEPTHS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH
0 3 6
MILES

SUTTER COUNTY CALIFORNIA

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J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 23 Arsenic_Well Depth.mxd 2/8/2012 2:39:39 PM bdemucha

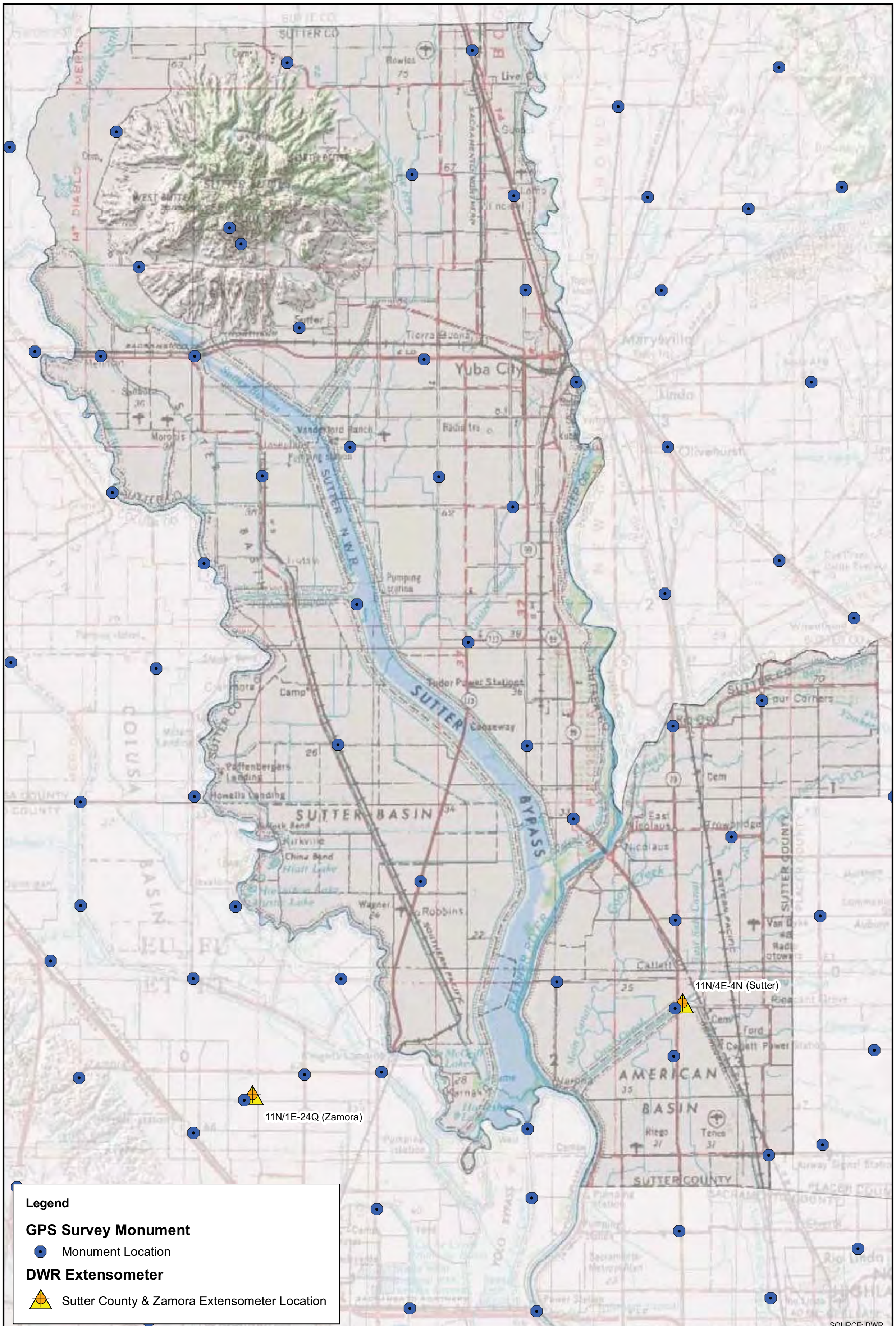

FIGURE 24
LAND SUBSIDENCE NETWORK
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH

0 1.5 3
MILES

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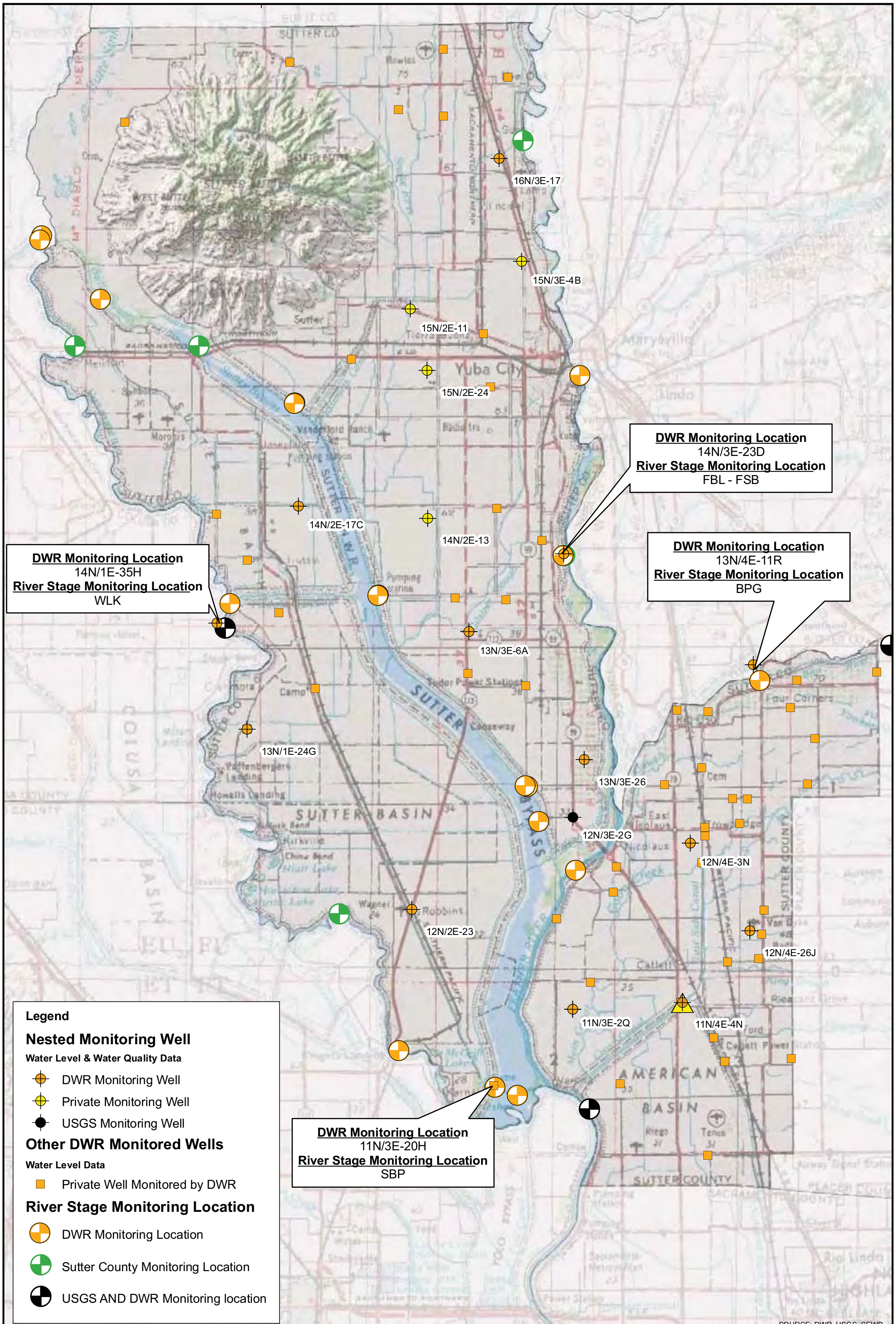

FIGURE 25
GROUNDWATER AND RIVER STAGE
MONITORING LOCATIONS

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH

0 1.5 3
Miles

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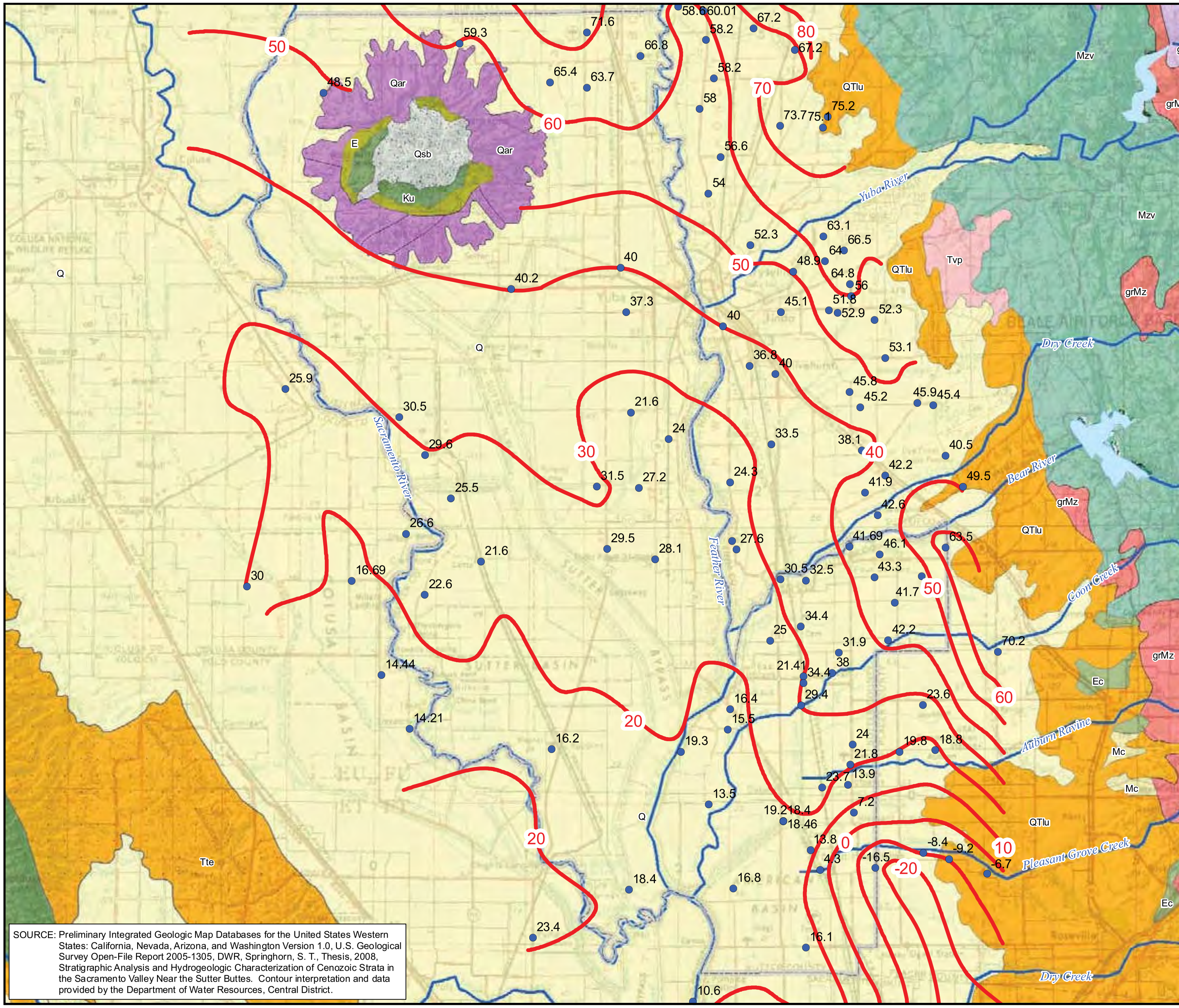
J:\Jobs\8337_SutterCounty\GIS\Tasks\20120116 Final Draft\Figure 25 Groundwater and River Stage Monitoring Locations.mxd 2/8/2012 2:46:51 PM bdemucha



SOURCE: Preliminary Integrated Geologic Map Databases for the United States Western States: California, Nevada, Arizona, and Washington Version 1.0, U.S. Geological Survey Open-File Report 2005-1305, DWR, Springhorn, S. T., Thesis, 2008, Stratigraphic Analysis and Hydrogeologic Characterization of Cenozoic Strata in the Sacramento Valley Near the Sutter Buttes. Contour interpretation and data provided by the Department of Water Resources, Central District.

FIGURE 26

RECHARGE AND GROUNDWATER ELEVATION CONTOUR MAP SPRING, 2009

SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012

NORTH

0 2 4
MILES

- Q - Recent Deposits
  - Qb - Basin Deposits
  - Qm - Modesto Formation
  - Qr - Riverbank Formation
- Qsb - Sutter Buttes Igneous Rocks
- Qar - Sutter Buttes Andesitic Rampart
- QTlu - Laguna Formation
- Tte - Tehama Formation
- Tvp - Andesite, Rhyolite
- Mc - Sandstone, Conglomerate
- Ec - Conglomerate, Sandstone
- E - Mudstone, Sandstone
- Ku - Sandstone, Mudstone
- J - Mudstone, Sandstone, & Slate
- um - Serpentinite
- Mzv - Volcanic, Metavolcanic
- gb - Gabbro, Diorite
- grMz - Granodiorite
- Sutter County
- DWR Monitored Wells Used for Contours
- Groundwater Contour of Equal Elevation (Feet, NGVD 29)

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Figure 27
Sutter County
Well Construction By Year

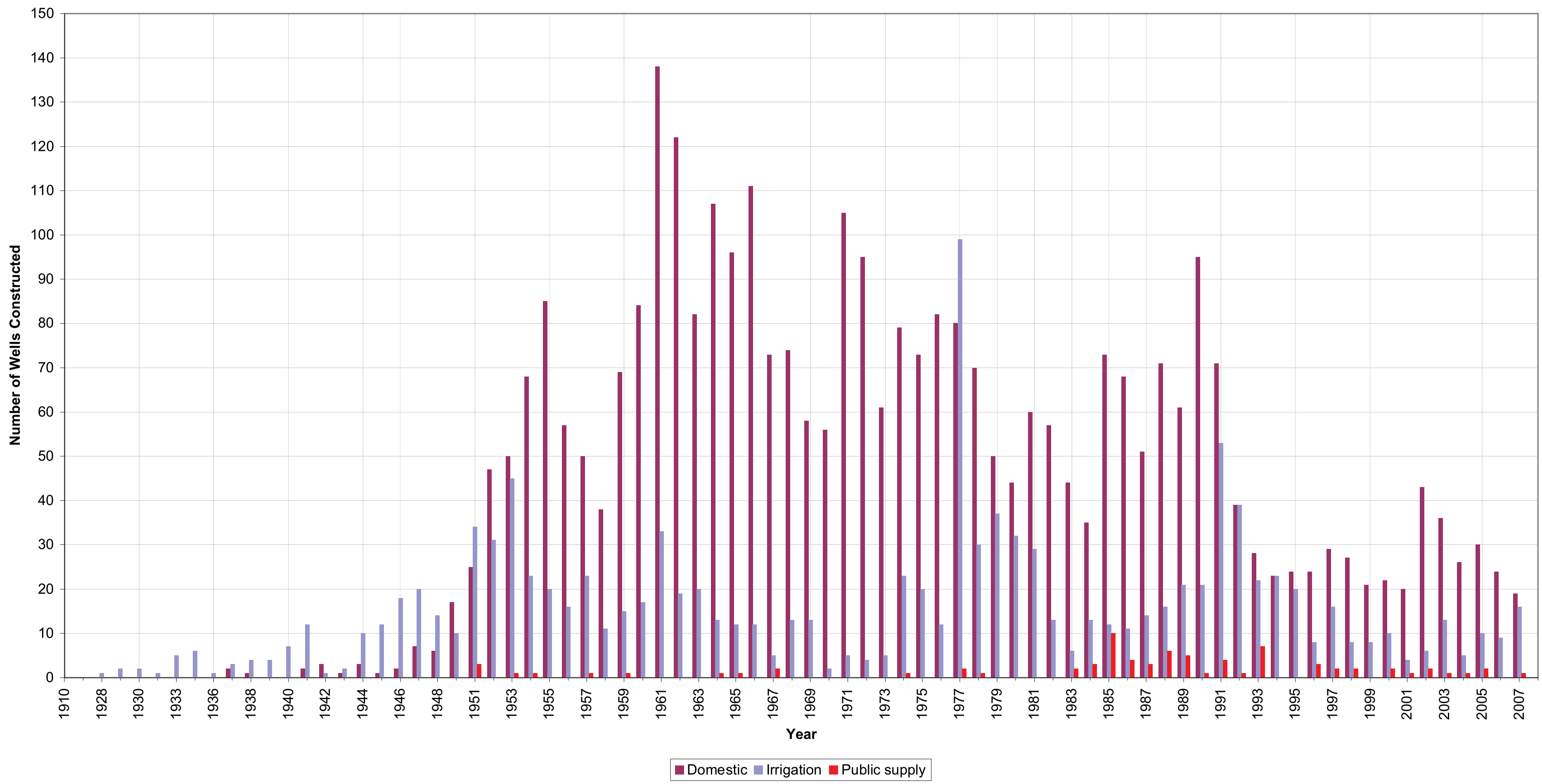
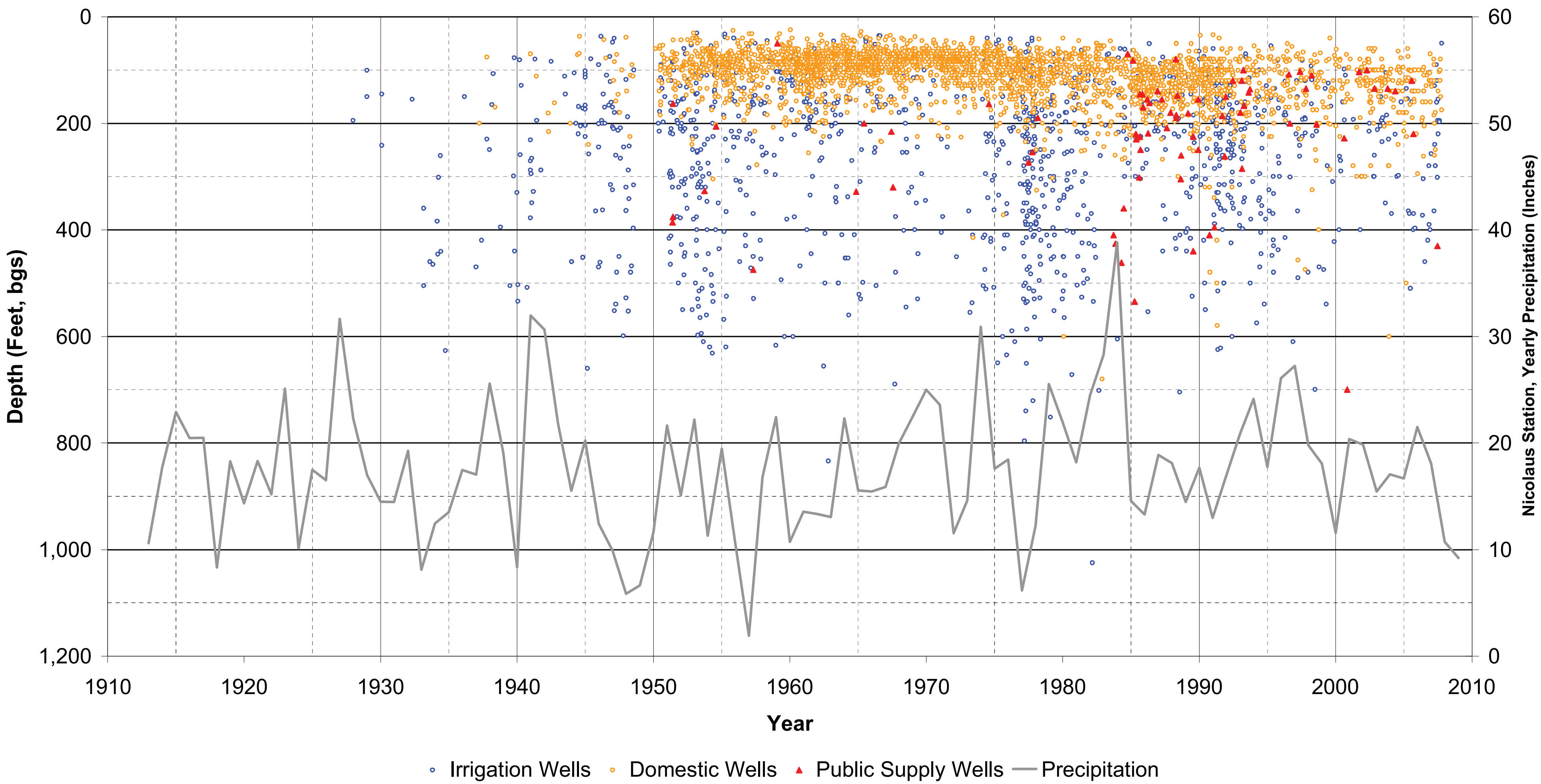


Figure 28
Sutter County
Historic Well Construction by Depth and Annual Precipitation



Toxic Water: A series about the worsening pollution in American waters and regulators' response

Examine whether contaminants in your water supply met two standards: the legal limits established by the Safe Drinking Water Act, and the typically stricter health guidelines. The data was collected by an advocacy organization, the Environmental Working Group, who shared it with The Times.

Browse All States
Understanding the Data
Related Story
Join the Discussion
All Stories in the Series: Toxic Waters »

View State...

Princeton Water District

Chart
Key
1 or more tests taken in the month
1 or more positive detections
1 or more tests above health limit
1 or more tests above legal limit

Princeton, California. Serves 408 people.

1 contaminant above legal limits

In some states a small percentage of tests were performed before water was treated, and some contaminants were subsequently removed or diluted. As a result, some reported levels of contamination may be higher than were present at the tap. Results shown are based on individual samples and may not indicate a violation of the Safe Drinking Water Act, which often occurs only after prolonged tests show concentrations above a legal limit.

					Number of Tests					
Contaminant	Average result	Maximum result	Health limit	Legal limit	Total #	Positive result	Above health	Above legal	Monthly Testing History Chart key at top of page	E.P.A. regulated
Arsenic (total)	12.50 ppb	17	2	10	1	1	1	1		Yes

Units: ppb: parts per billion, pCi/L: picocuries per liter, ppm: parts per million, mrem/yr: millirems per year, MFL: million fibers per litre

Additional Resources

View E.W.G.'s Report for This System »
Note: The Times' analysis may differ from the Environmental Working Group (Learn More)
View E.P.A. Violations »

Source: The Environmental Working Group (**About this data**)

System operators should contact The Times to report inaccuracies or comments.
Charles Duhigg, Matthew Ericson, Tyson Evans, Brian Hamman, Derek Willis

DEL ORO WATER COMPANY
DELIVERING NATURE'S PRECIOUS RESOURCE

November 3, 2015

Advice Letter No. 424

TO THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA

Del Oro Water Company, Inc. on behalf of its Walnut Ranch District (District) hereby transmits for filing the following Advice Letter No. 424 to recover costs associated with both the District's reimbursement of City of Colusa fees incurred in contract negotiations for the Emergency Transmission Intertie Project as well as District costs incurred with the Colusa Industrial Park Intertie Project. Changes in the respective District tariff schedule are attached hereto:

Cal. P.U.C. Sheet No.	Title of Sheet	Schedule No.	Canceling Cal. P.U.C. Sheet No.
-W	Schedule No. WR-2 (cont.) Residential Flat Rate Service	WR-2	1701-W
-W -W	Table of Contents		-W -W

Purpose

DOWC hereby submits this filing and the attached calculations **[Exhibit A]** in support of its claim for reimbursement of the costs associated with both the Emergency Transmission Intertie Project with the City of Colusa as well as those incurred with the Colusa Industrial Park Intertie Project. All costs have been tracked in DOWC's Preliminary Statement Paragraph S "Del Oro Water Company Extraordinary Events Emergency Water and/or Supplemental Water Memorandum Account (EEEW/SWMA)" **[Exhibit B]**. This account tracks costs which are incurred from time-to-time in purchasing water from outside agencies and/or interconnecting to outside agencies (either temporarily or permanently) in order to facilitate delivery of water for any of DOWC's districts. The EEEW/SWMA for the District has tracked all costs **[Exhibit C]** totaling $93,845.29 specifically relating to contract negotiations with the City regarding the Emergency Transmission Intertie Project as well as the legal and engineering costs of the proposed Colusa Industrial Park Intertie Project.

Background

CITY OF COLUSA/DOWC WALNUT RANCH EMERGENCY TRANSMISSION INTERTIE PROJECT

On August 18, 2008 Del Oro Water Company (DOWC), on behalf of its Walnut Ranch District, contacted Mr. Rob Hickey, then City Manager for the City of Colusa, and requested the City Council consider a permanent intertie to their system as an alternative to the Colusa Industrial Park Intertie Project which was suspended while the customers and the City explored the City purchasing the District's assets. DOWC thought an intertie with the City would provide its customers with potable water at the most reasonable cost. The City's ultimate position was that an intertie could only be used on an emergency basis and not considered a permanent solution to the water issues within the District.

As part of the agreement executed on February 3, 2009 with the City **[Exhibit D]**, DOWC agreed to pay all City costs in bringing the emergency contract to fruition. A recent internal audit has found the costs totaling $8,184.11 were not addressed for reimbursement to the District in discussions with the City. These costs are included in the total requested reimbursement.

THE COLUSA/DOWC INDUSTRIAL PARK INTERTIE PROJECT

In 2005, the District began working on an intertie project with the Colusa Industrial Park knowing the water issues within the District required an alternative source. Efforts were also required as a response to The State Water Resources Control Board's (formerly The State Department of Public Health) Compliance Order No. 01-21-10 on July 15, 2010 ordering the District to achieve compliance with the maximum contaminant level for Arsenic, which the District's water supply exceeded. Tremendous efforts and cooperation between the parties resulted in the Colusa Industrial Park Intertie Project **[Exhibit E]**, approved by CPUC Res. W-4761, dated May 7, 2009 **[Exhibit F]**, but which was stalled due to customers' desire to annex to the City of Colusa. In that regard, the District suspended work on the project and the project was classified in CPUC Res.W-4873 **[Exhibit G]** as "... currently suspended Industrial Park Intertie Project...". Point being made that the project was not disapproved but reimbursement was on hold pending the customers' and City's efforts to have the City of Colusa acquire the District.

Now comes forth the City of Colusa, as of October 29, 2015, with an officially tendered 'sole tentative offer' on fair market value as well as their recognition of the Purchase Water Surcharge (Advice Letter No. 366-A). However, we believe we have a disconnect regarding the recovery process for costs incurred in bringing the Colusa Industrial Park Intertie Project to a shovel ready status, and DOWC's entitlement to reimbursement for legal and associated appraisal costs to date.

Therefore, The District proposes to collect the $93,845.29 reflecting both the Emergency Transmission Intertie Project and the Colusa Industrial Park Intertie costs in a surcharge of $20.58 per customer per month for sixty (60) months or until the full amount is collected.

Requested Effective Date

DOWC is submitting the attached as a Tier 3 filing and requests that it become effective at the earliest date as the Commission's decision is critical in negotiating with the City of Colusa.

Notice and Service

All customers and interested parties will be notified of the request for reimbursement of costs associated with the Colusa Industrial Park Intertie Project for Commission consideration and approval and its rate impact by way of direct mail on Tuesday, November 3, 2015 **[Exhibit H]**.

File a PROTEST:

A protest is a document stating that you object to the utility receiving all or some part of its request. If you wish to file a protest, you must state the facts constituting the grounds for the protest, how the advice letter affects you, and the reasons why you believe the whole advice letter, or part of it, is not justified.

If the protest requests an evidentiary hearing (an evidentiary hearing is a legal proceeding held before an administrative law judge at the Commission to obtain evidence), your protest must state the facts you would present at the evidentiary hearing to support your request for a complete or a partial denial of the advice letter. The filing of a protest does not ensure that an evidentiary hearing will be held. The decision whether or not to hold an evidentiary hearing will be based on the contents of the protest.

File a RESPONSE:

A response is a document that does not object to the request sought in the application, but nevertheless, presents information you believe would be useful to the Commission in acting on the application.

Whether you wish to file a PROTEST or send a RESPONSE you must:

- Send a copy of your document to the utility.
- A protest must be emailed or mailed (email preferred) within (20) days of the date you received this notice.

The utility must respond to your protest or response within five (5) days. All protests or responses to this filing should be sent to:

California Public Utilities Commission, ***and***
Water Division
505 Van Ness Avenue
San Francisco, California 94102
E-Mail : water_division@cpuc.ca.gov

Director of Community Relations
Drawer 5172
Chico, CA 95927
(530) 717-2509 / Fax: (530) 894-7645
E-Mail: communityrelations@delorowater.com

If you have not received a reply to your protest within ten (10) business days, contact Del Oro Water Company at 1-530-717-2509.

This filing will not cause withdrawal of service nor conflict with any other schedule or rule.

A copy of Del Oro Water Company's filing may be inspected in its business office: 426 Broadway, Suite 301, Chico, California 95928 or by visiting the website at www.delorowater.com. Further information may be obtained from the utility at its business office or from the Commission at the above address.

Del Oro Water Company, Inc.

Janice Hanna

JANICE HANNA
Director, Corporate Accounting

Attachments

Del Oro Water Company- Walnut Ranch District Consolidation

Updated on: February 9, 2018

County: Colusa
Population: 182
Challenges: Drinking water standard violation for Arsenic
Consolidation date: April 6, 2017

The Del Oro Water Company - Walnut Ranch District served a population of 182 customers. The water system had one well which exceeded the maximum contaminant level for arsenic and physically collapsed, leaving the Walnut Ranch Subdivision to rely on an emergency intertie with the City of Colusa (City).

Figure 1. Old Well and Associated Equipment

A consolidation project was funded by a $500,000 State Revolving Fund planning grant which included the following- an engineering report, CEQA/NEPA[1] documentation, annexation agreements, and plans and specifications for needed distribution upgrades.

The City acquired the assets of Del Oro Water Company - Walnut Ranch District in April 2017. The consolidating system is now moving forward to replace distribution pipelines under a construction project with the State Water Resources Control Board's Division of Financial Assistance.

Even with the City's water rates and a temporary assessment on the customers for required upgrades, the customers are paying $20 less per month under the consolidation compared to when the system was operating alone. The figure shows the well and sand separation, and pressure tank equipment that is no longer required to be operated and maintained by the subdivision adding the reduction of their monthly bills.

[1] California Environmental Quality Act (CEQA)/ National Environmental Policy Act (NEPA)

From: Karen Biane
To: Mary Fahey
Subject: Sub-watershed public comments
Date: Thursday, December 17, 2020 2:56:52 PM
Attachments: Colusa subwatershed comments.docx

Dear Ms. Fahey:

My name is Karen Biane. My family is a "stakeholder" in the Glenn County subwatershed basin. I have had the opportunity to attend the online December 9, 2020 Colusa Glenn Subbasin SGMA, and December 14, Butte SGMA meetings. I found both sets of meetings to be worth attending. At the conclusion of the meetings, public input was encouraged, which is why I am writing.

My background is in the financial services industry, and international bank management training. That background is what has compelled me to write. I have attached a memo outlining my commentary on specific areas about the presentations and plans.

I am aware of the incredible complexity and challenges the planning and implementation of the program will involve. The ideas presented are designed to potentially improve the communications to, and understanding by, the water community.

I will look forward to the December 22, 2020 meeting. Please feel free to contact me with any questions. My email is: knbiane@gmail.com, home phone: 916-791-1912.

Respectfully submitted,

Karen Biane
knbiane@gmail.com

From: Ben King <bking@pacgoldag.com>
Sent: Tuesday, February 2, 2021 3:06 PM
To: Ceppos, David M <dceppos@csus.edu>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; Ben King <bking@pacgoldag.com>
Subject: Determination of the Location of the Willows Fault Near the City of Colusa

Hi David,

Can you forward this email to Mr. Clark and Mr. Loy

I believe that it is important to have the correct location of the Willows Fault regarding the proximity of the Fault to the City of Colusa. As you will see in the attached Figure 7 from the Sutter County GMP it looks like a wishbone like structure near the City with one fork trending south east away from the City on the east side of the Sacramento River and another fork on the west side of the River nearer to the City trending more in a north south direction.

The HCM identifies the north south fork as an "unnamed Anticline" and cites several sources including the (USGS Paper 1359) Harwood and Helley report as supplemented by the California Department of Natural Resources. The Sutter GMP cites a USGS Geologic Map dated from 2005 which possibly may be more precise? Harwood and Helley have a figure (as attached) which is hard to decipher as to its location to the City or the River but seems to indicate that the fork begins at the 39.15 latitude which would be south of the Colusa Airport but north of Meridian.

The reason I think it is important to get the best information on this fork in the Willows Fault is the potential for the movement of arsenic contamination along the Willows Fault from the desorption of arsenic from the metal and iron oxides in the volcanic rock of the Sutter Buttes. So far the public water supply for the City does not seem to be contaminated but the location of this fork may be problematic for the future risk profile.

There is also the potential for the movement of the anoxic seawater from the Buttes formation via the Willows Fault but that is less of the concern because it relates more to potential degradation in potability rather than arsenic toxicity.

Thank you for your time and consideration of this matter.

Best Regards,

Ben

CHICO MONOCLINE

The Chico monocline (fig. 13) is a northwest-trending, southwest-facing flexure that bounds the northeast side of the Sacramento Valley between Chico and Red Bluff. East of the monocline, Pliocene volcanic rocks of the Tuscan Formation dip less than 5° SW., but bedding steepens to 20° or more along the monoclinal flexure where the Tuscan dips beneath Quaternary deposits of the valley. The trace of the monocline is characterized by a complex surface pattern of anastomosing fault strands

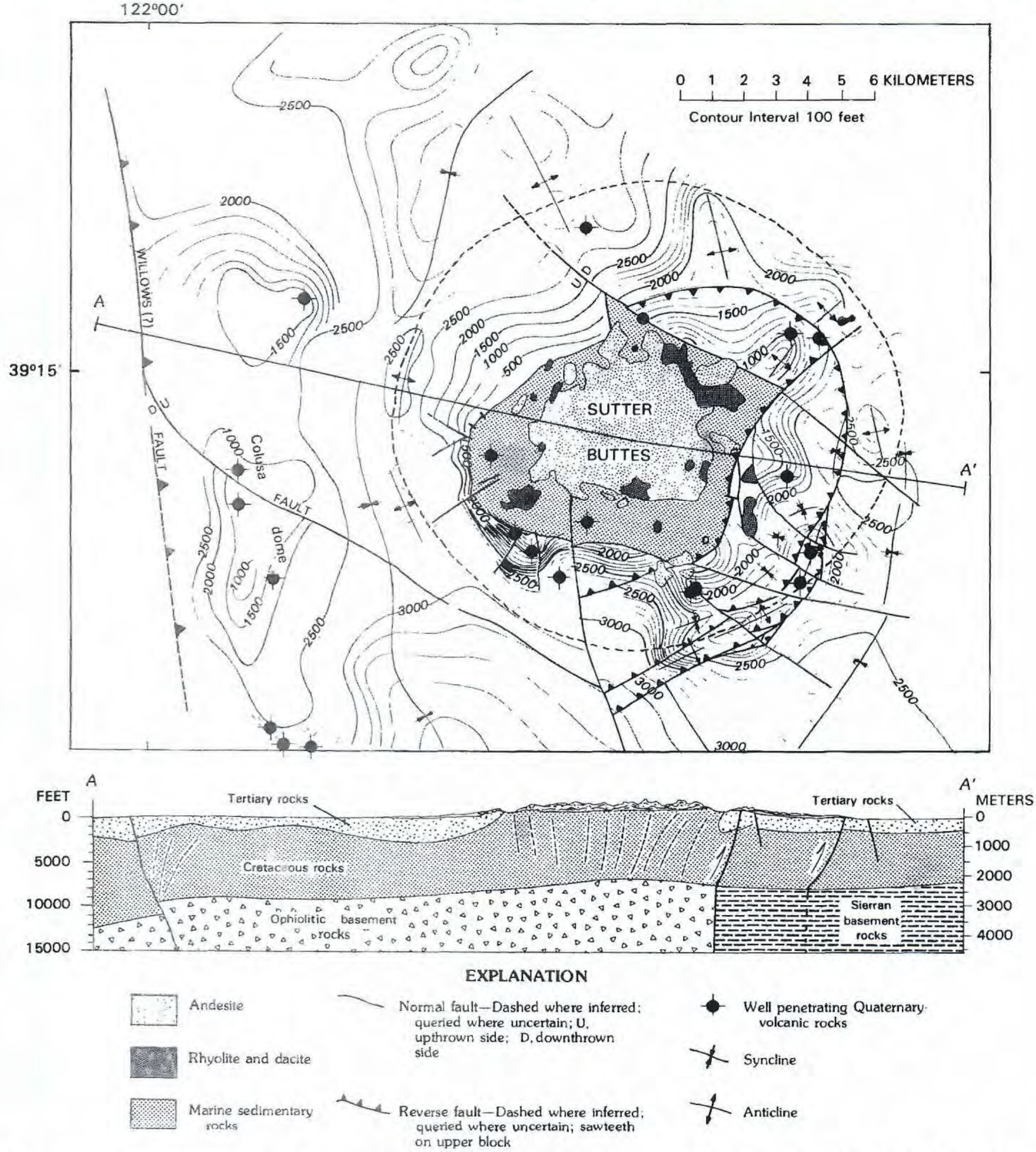


FIGURE 12.—Structure contour map of area around Sutter Buttes, modified from Williams and Curtis (1977, fig. 11) with data from Redwine (1972) and from our examination of electric logs in area of buried Colusa dome. Structure contours in feet; datum is top of the Kione sand of local usage (Williams and Curtis, 1977). Dashed circle on map marks approximate outer limit of rampart beds on valley floor; thin dashed lines on section represent schematic paths of magma injection.

Unit	*Age/Age range* (*m.y.*)	*Reference*
Rockland ash bed	0.4-0.45	Sarna-Wojcicki and others (1985); Meyer and others (1980)
Red Bluff Formation	0.5-1.0	Harwood and others (1981)
Olivine basalt of Deer Creek	1.09	Harwood and others (1981)
Ishi Tuff Member of the Tuscan Formation	2.6	Harwood and others (1981; unpublished data, 1985)
Volcanic rocks of Sutter Buttes	1.4-2.4	Williams and Curtis (1977)
Nomlaki Tuff Member of the Tuscan and Tehama Formations	3.4	Evernden and others (1964)
Putah Tuff Member of the Tehama Formation	3.4	Sarna-Wojcicki (1976)

With the exception of the Dunnigan Hills, the structural domains shown in figure 23 become progressively younger northward through the valley. Late Cenozoic deformation in the Dunnigan Hills domain apparently overlapped that in the Corning domain, but the respective styles of deformation and the inferred stress regimes discussed in a later section differ significantly. This point emphasizes the fact that the structural domains include tectonic features that are homogeneous in time and style of deformation as far as we can determine. To a certain extent, the ages of the structural domains reflect the distribution of the time-stratigraphic units used to identify the major late Cenozoic deformation in a domain. It may be possible to subdivide some domains as more information on the distribution of the younger time-stratigraphic units becomes available. Furthermore, it is important to note that ascribing an age to the late Cenozoic deformation in a domain does not imply that all deformation necessarily began or ended within that time. Many late Cenozoic structural features in the valley formed over earlier structures in the upper Mesozoic or Tertiary rocks, and thus they owe their existence, in part, to tectonic heredity. In some areas, historic low-magnitude earthquakes can be identified with specific structural features such as the Battle Creek fault zone (Bolt, 1979) and Corning fault (Marks and Lindh, 1978), indicating that strain is currently being released on these structures.

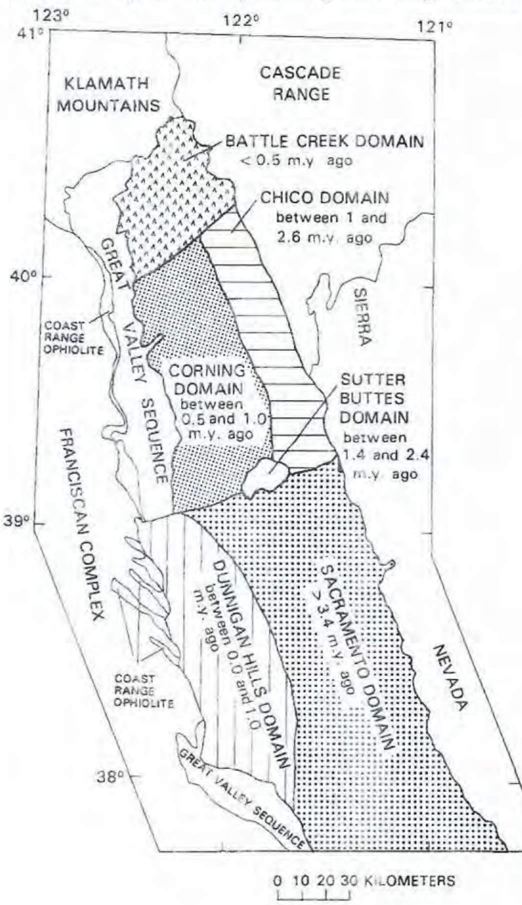


FIGURE 23.—Structural domains in Sacramento Valley. Numbers under domain names give duration or age of deformation that produced late Cenozoic structures in that domain.

SACRAMENTO DOMAIN

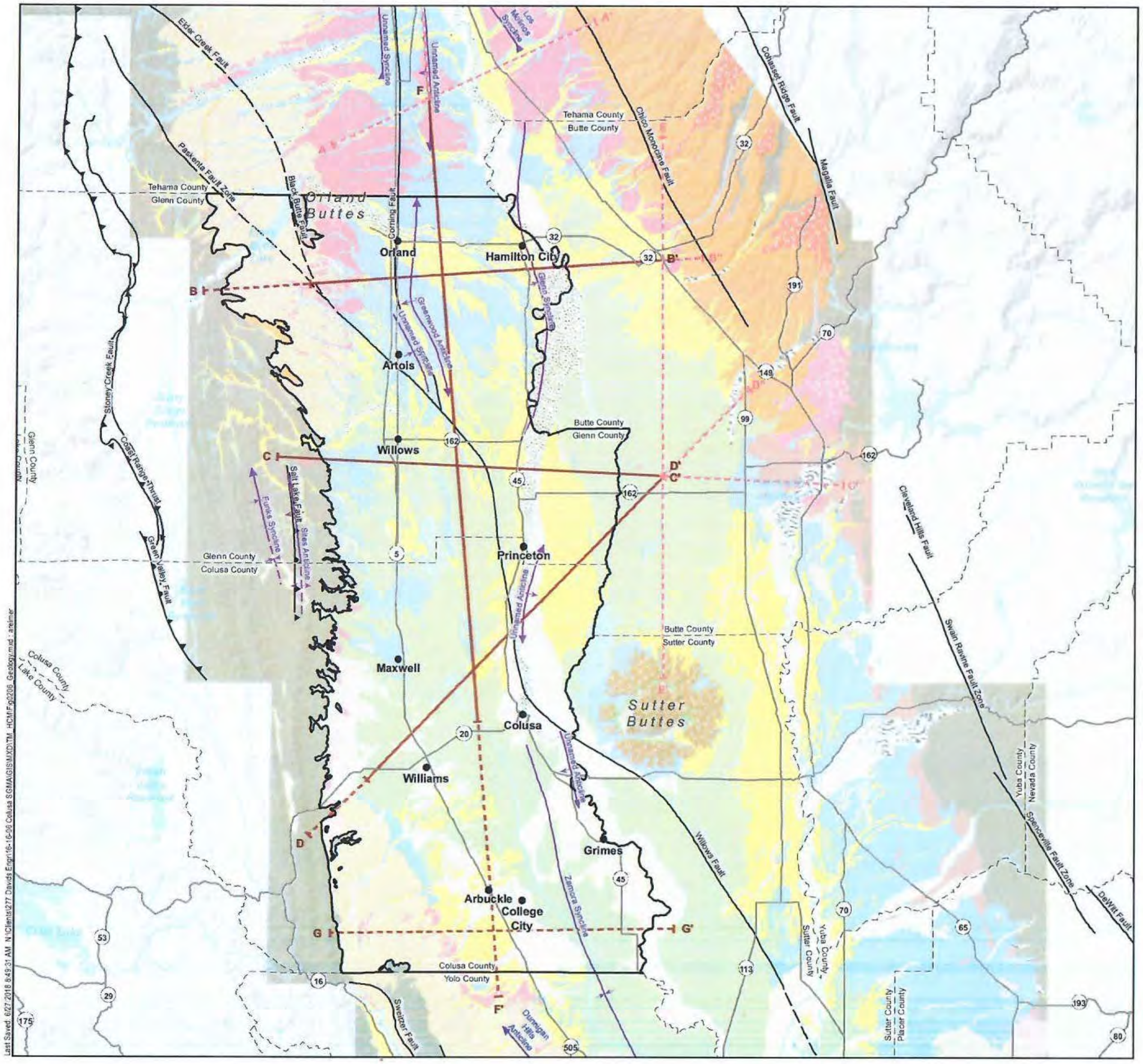
The Sacramento domain includes the Stockton fault, the Midland fault, the Thornton anticline, and the possible southeast extension of the Willows fault and other unnamed northwest-trending faults southeast of Sutter Buttes. None of these structures appear to offset or deform late Cenozoic alluvial deposits that are younger than the Nomlaki Tuff Member (figs. 7-10; Silcox, 1968; Teitsworth, 1968).

The minimum age of deformation is difficult to determine. If the Markley submarine canyon was localized, in part, by movement on the southeast extension of the Willows fault, as suggested by figures 8 and 9, then major deformation occurred in the domain in the middle Tertiary and could be as young as early Miocene, which is the upper age of the Markley canyon fill (Almgren, 1978). However, the Pliocene Laguna Formation, which contains the Nomlaki Tuff Member near its base just east of Marysville (Bussaca, 1982), does not appear to be offset in this domain; therefore, we conclude that deformation is older than 3.4 m.y. Upper Cretaceous rocks indicate syndepositional offset on the Stockton fault (Teitsworth, 1968) so the maximum age of deformation is Late Cretaceous.

The Willows fault north of Sutter Buttes (fig. 3) and the faults in Capay Valley (fig. 20) also show protracted deformation, ranging in age from Late Cretaceous to the middle Tertiary, that undoubtedly was contemporaneous with deformation in the Sacramento domain.

SUTTER BUTTES DOMAIN

The complex pattern of folds and faults at Sutter Buttes and the buried Colusa dome was interpreted by Williams



Symbology

- Northern Sacramento Valley Geology Cross Section Used for Preliminary Hydrogeologic Conceptual Model
- Section Extension or New Cross Section
- Northern Sacramento Valley Geology Cross Section Not Used for Preliminary Hydrogeologic Conceptual Model
- Study Area

0 4 8
Scale in Miles

N

Geologic Structures

- Anticline
- Syncline
- Plunging Anticline
- Plunging Syncline
- Doubly Plunging Anticline
- Double Plunging Syncline
- Fault
- Thrust Fault

Geologic Units

- Stream Channel Deposits (Holocene)
- Alluvial Deposits (Holocene)
- Basin Deposits (Holocene)
- Landslides (Quaternary)
- Modesto Formation (Pleistocene)
- Riverbank Formation (Pleistocene)
- Red Bluff Formation (Pleistocene)
- Turlock Lake Formation (Pleistocene)
- Older Gravel Deposits (Pleistocene - Pliocene)
- Rockland Ash Bed (Pleistocene)
- Volcanic Rocks and Lacustrine Deposits of Sutter Buttes (Pleistocene - Pliocene)
- Basaltic Rocks (Pleistocene - Pliocene)
- Tehama Formation (Pliocene)
- Nomlaki Tuff Member (Pliocene)
- Putah Tuff Member (Pliocene)
- Tuscan Formation (Pliocene)
- Laguna Formation (Pliocene)
- Sutter Formation of Williams and Curtis (1977) (Pliocene - Oligocene)
- Channel Deposits (Pliocene - Miocene)
- Mehrten Formation (Pliocene - Miocene)
- Lovejoy Basalt (Miocene)
- Ione Formation (Eocene)
- Sedimentary Rocks in Sutter Buttes Area (Eocene)
- Metamorphic, Igneous, and Sedimentary Rocks (pre-Paleogene)
- Tailings

Source:

1. California Department of Water Resources, 2014, Geology of the Northern Sacramento Valley: prepared by the California Department of Water Resoures Northern Region Office, Groundwater and Geologic Investigations Section, updated September 2014.
2. Helley, E.J. and Harwood, D.S., 1985, Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1790, scale 1:62,500, GIS geodatabase.
3. Jennings, C.W. and Strand, R.G., 1960, Geologic Map of California, Olaf P. Jenkins Edition, Ukiah Sheet: Department of Natural Resources Division of Mines and Geology, third printing 1992, scale 1:250,000.
4. Koenig, J.B., 1963, Geologic Map of California, Olaf P. Jenkins Edition, Santa Rosa Sheet: California Department of Natural Resources Division of Mines and Geology, scale 1:250,000.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Notes:

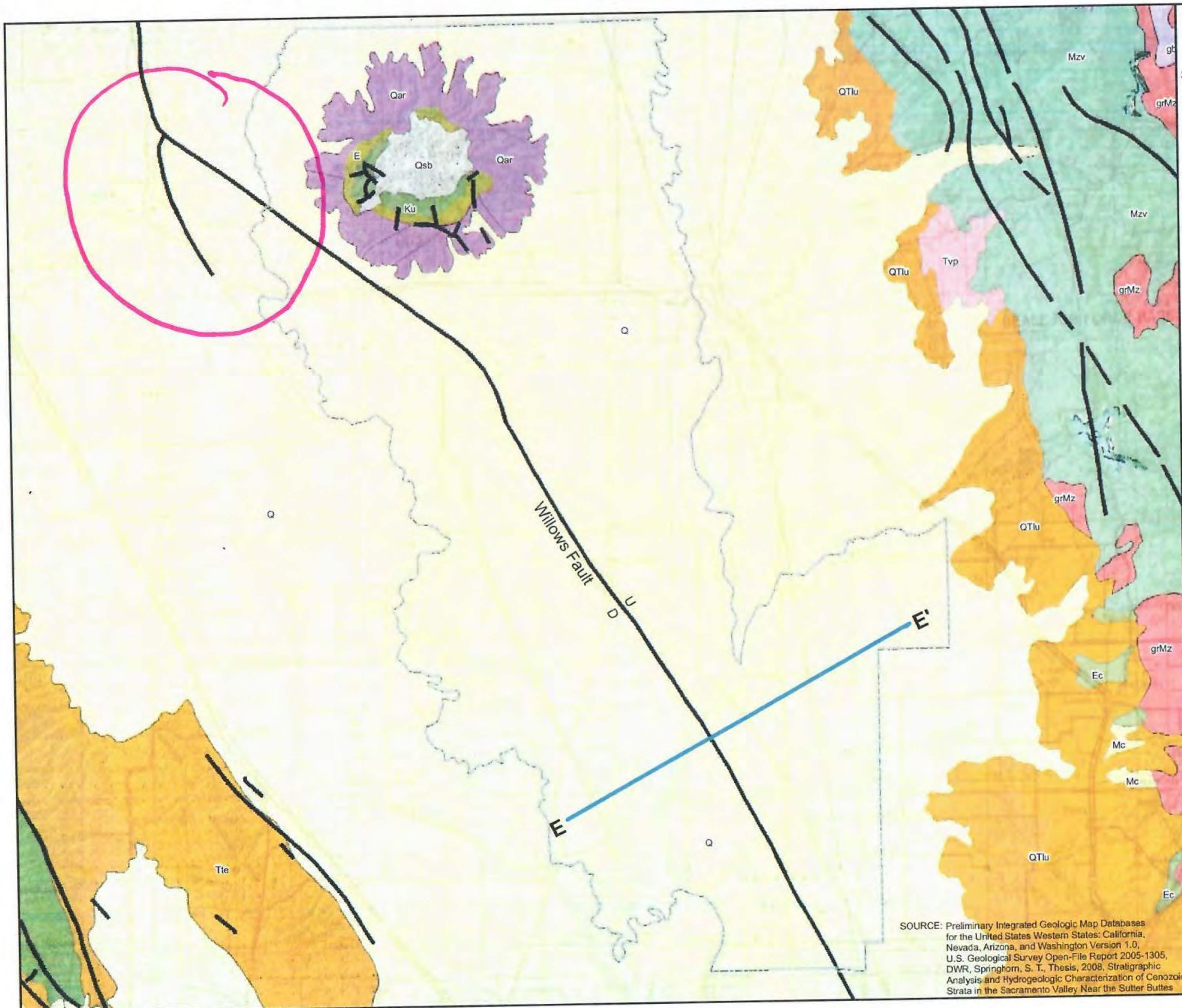
1. The Helley and Harwood mapping is used where available and is supplemented with geologic mapping from the California Department of Natural Resources Division of Mines and Geology sheets to cover the entire study.
2. Geologic structures are dashed where approximated.

Figure 2-6

Geologic Map

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

FIGURE 7
SIMPLIFIED SURFACE GEOLOGY AND FAULTS
SUTTER COUNTY GROUNDWATER MANAGEMENT PLAN
FEBRUARY 2012



LEGEND

- Q - Recent Deposits
  - Qb - Basin Deposits
  - Qm - Modesto Formation
  - Qr - Riverbank Formation
- Qsb - Sutter Buttes Igneous Rocks
- Qar - Sutter Buttes Andesitic Rampart
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- E - Mudstone, Sandstone
- Ku - Sandstone, Mudstone
- J - Mudstone, Sandstone, & Slate
- um - Serpentinite
- Mzv - Volcanic, Metavolcanic
- gb - Gabbro, Diorite
- grMz - Granodiorite
- Fault
- Fault Displacement - U, upthrown side; D, downthrown side
- Counties
- Simplified Conceptual Geologic Cross Section Line (See Figure 8)

SOURCE: Preliminary Integrated Geologic Map Databases for the United States Western States: California, Nevada, Arizona, and Washington Version 1.0, U.S. Geological Survey Open-File Report 2005-1305, DWR, Springhorn, S. T., Thesis, 2008, Stratigraphic Analysis and Hydrogeologic Characterization of Cenozoic Strata in the Sacramento Valley Near the Sutter Buttes

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3301 C Street, Bldg. 100-B Tel: 916.341.7760
Sacramento, CA 95816 Fax: 916.341.7767

From: Ben King <bking@pacgoldag.com>
Sent: Monday, February 8, 2021 4:54 PM
To: Ceppos, David M <dceppos@csus.edu>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; Ben King <bking@pacgoldag.com>
Subject: California Geological Survey - Willows Fault Location Near City of Colusa

Hi David,

Can you send this follow up email regarding the location of the Willows Fault and its location near the City of Colusa to Mr. Loy and Mr. Clark.

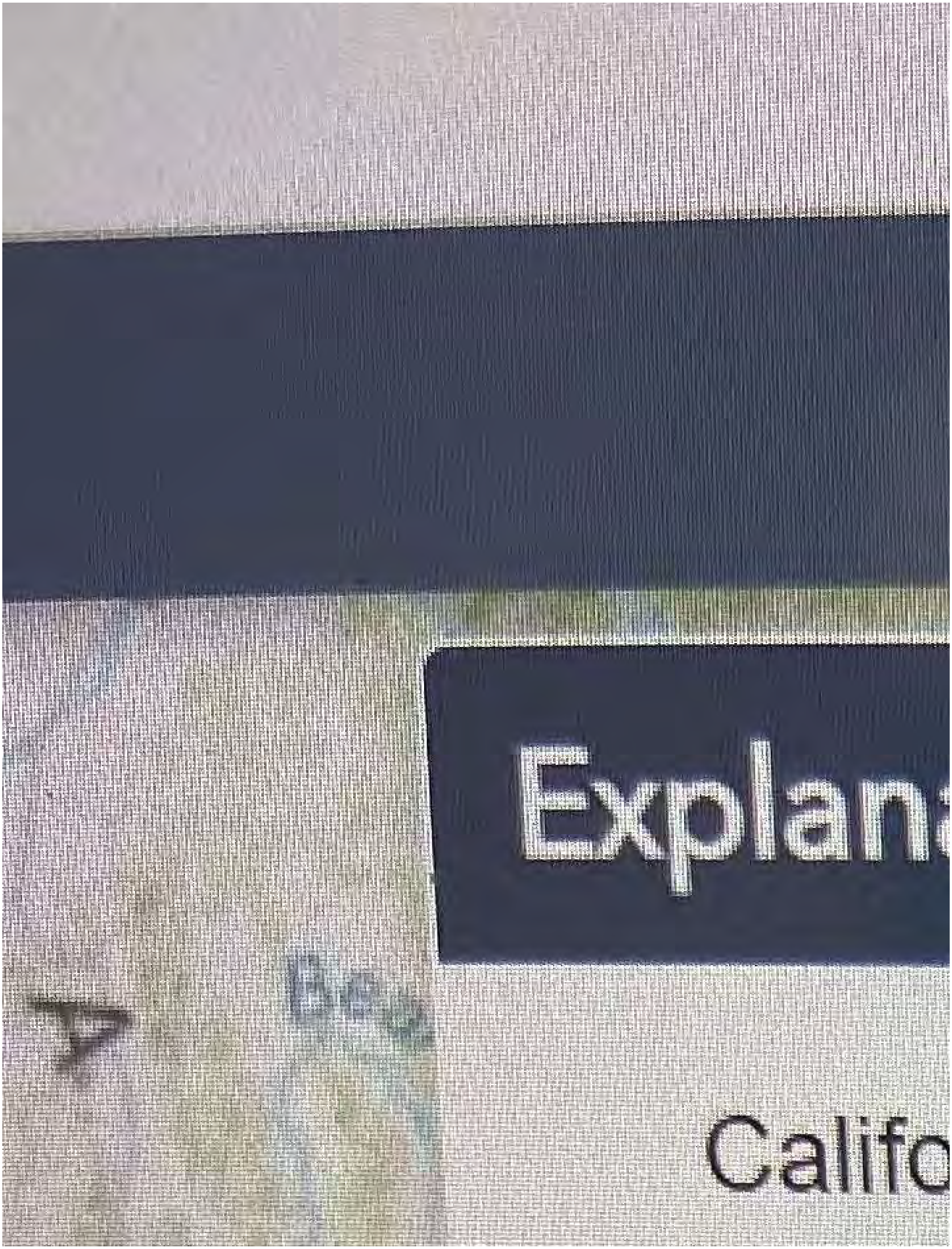
The link for the California Geological Survey is below. The location of the Willows Fault appears to have a fork north of the Colusa State Park and ironically appears to run under the Colusa County Courthouse. I have included three photos from the link.

https://maps.conservation.ca.gov/cgs/fam/app/

I believe this is a different location than set out in the Geologic Figure in the HCM. It seems to be very close to the City of Princeton and the Colusa Rancheria. It actually runs through Colusa and towards Grimes and Meridian along Hwy 20. As I mentioned before I wanted to raise the issue of the Fault as the mechanism whereby the arsenic and seawater contamination from the Sutter Buttes may be translocating.

Thank you for your time and consideration

Ben King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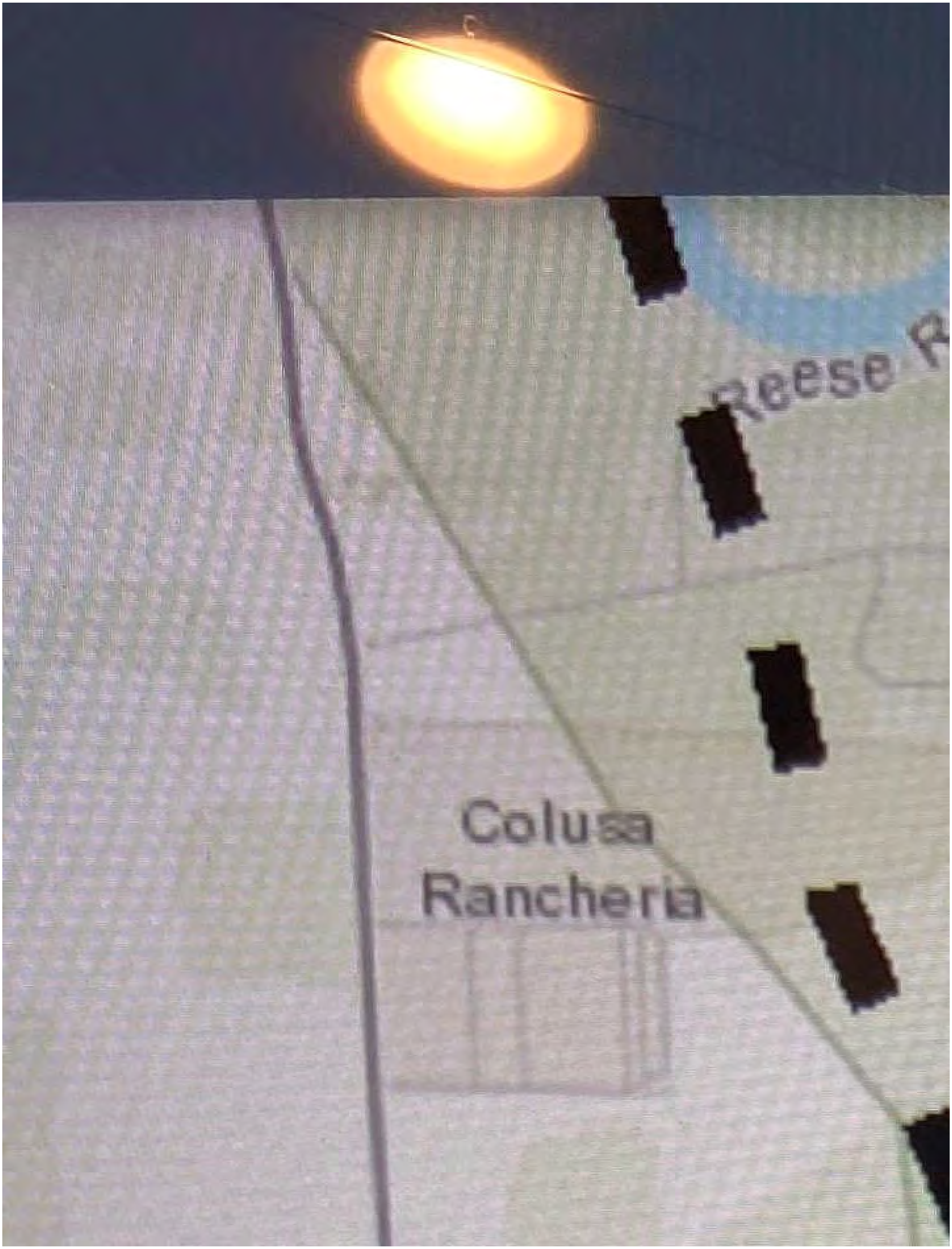
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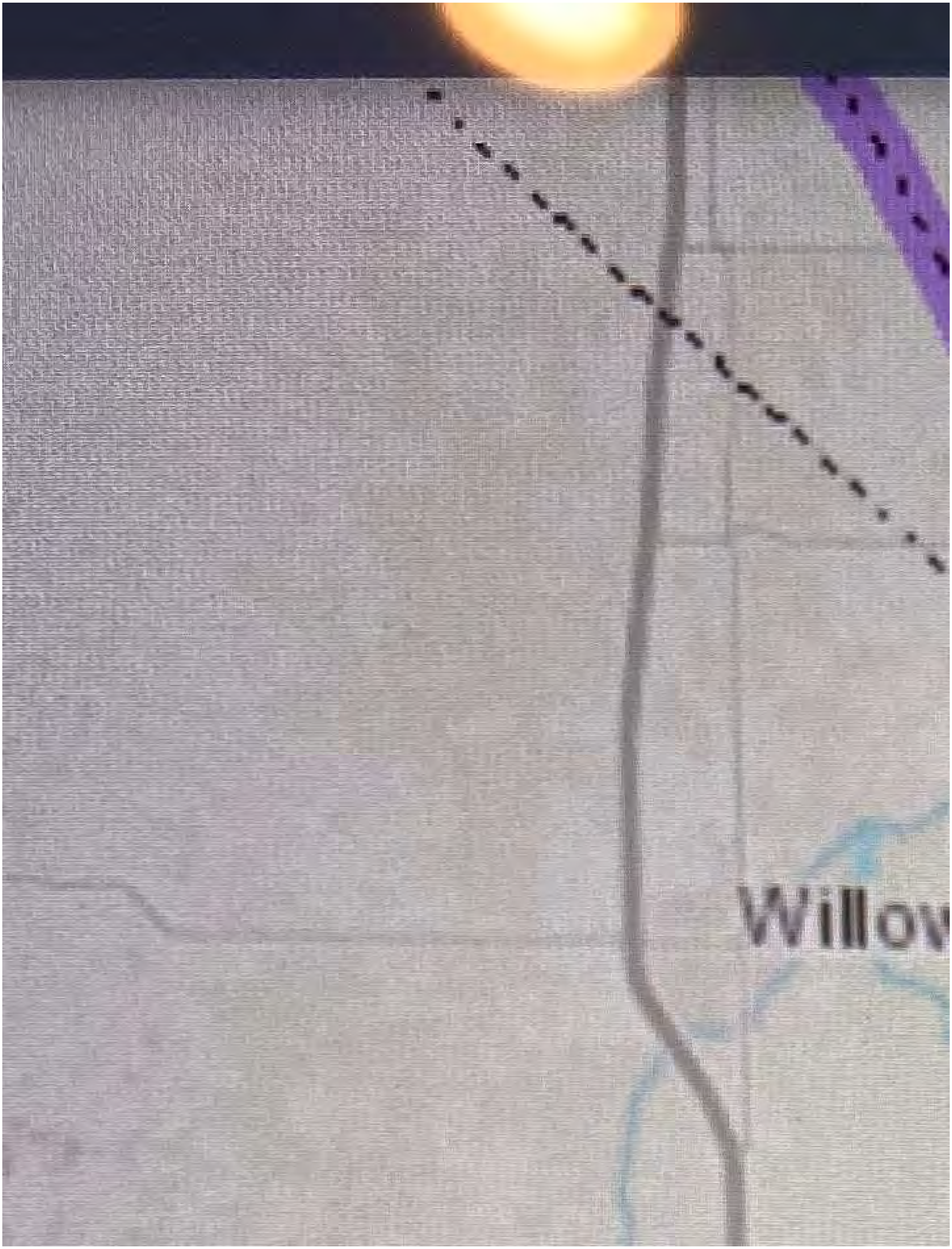
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From: Byron Clark
Sent: Friday, January 22, 2021 11:03 AM
To: Matt Jones <Matt@tnpfarms.com>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; 'Lisa Hunter' <LHunter@countyofglenn.net>
Subject: RE: Follow Up Regarding Colusa Subbasin GSP Questions

Hi Matt,

I wanted to follow up from our discussion in December and provide a map and kmz of the water budget subareas used to develop the model and associated water budgets for the basin (see link below). As discussed, these do not represent management areas but rather subareas within the basin based on water supplier boundaries, county boundaries, and other considerations.

I agree regarding management areas being a tough discussion. The SGMA regulations do not provide a lot of detail regarding the use of management areas, and they have been used differently in many basins. Also, I completely agree the basin is interconnected.

Regarding recharge and banking, I wanted to reiterate that we fully anticipate considering in-lieu and direct recharge projects as part of GSP development and implementation. There seem to be substantial opportunities for the use of additional surface water, particularly in wet years which we are exploring.

Finally, the link includes maps of physical characteristics of the subbasin and jurisdictional boundaries that were presented to the TACs on January 8 that may be helpful.

https://app.box.com/s/eidbnyyqii3ay2rk87etlcse4jzuzcct

Regards,

Byron

Byron Clark, P.E. | Supervising Engineer | Davids Engineering, Inc.
1772 Picasso Avenue, Suite A, Davis, CA 95618 | office 530.757.6107 x106

From: Matt Jones <Matt@tnpfarms.com>
Sent: Wednesday, January 13, 2021 10:59 AM
To: Byron Clark <byron@davidsengineering.com>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; 'Lisa Hunter' <LHunter@countyofglenn.net>
Subject: RE: Follow Up Regarding Colusa Subbasin GSP Questions

Wanted to follow up regarding "management areas". It is a tough discussion and should include laying out the facts regarding areas of concern. I vague statement regarding an area does not do anybody justice and leads to speculation and possibly inaccurate conclusions. The attached maps paint a clearer picture of "areas" of concern, but more importantly it emphasizes how our basin is interconnected and impacts of "areas" not within the "management areas"?

I would also like to follow up regarding recharge and banking. I am trying to get an understanding of how it will play a roll in the GSP or if it will be addressed within the GSP.

Regards;

From: Byron Clark <byron@davidsengineering.com>
Sent: Tuesday, December 15, 2020 12:19 PM
To: Matt Jones <Matt@tnpfarms.com>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; 'Lisa Hunter' <LHunter@countyofglenn.net>
Subject: Follow Up Regarding Colusa Subbasin GSP Questions

Hi Matt,

Thank you for your questions below regarding the water budget development for the Colusa GSP. Would you be available for a call to make sure I understand your questions to make sure I respond in a supportive manner?

Thank you,

Byron

Byron Clark, P.E. | Supervising Engineer | Davids Engineering, Inc.
1772 Picasso Avenue, Suite A, Davis, CA 95618 | office 530.757.6107 x106

From: Matt Jones <Matt@tnpfarms.com>
Date: December 10, 2020 at 3:59:35 PM PST
To: Mary Fahey <mfahey@countyofcolusa.com>
Subject: GSP

Good meeting and information today.
You are all doing a great job!
I know there is still a long way to go.

I have 2 points of clarification or questions;

1) The 38 subbasins. How can we access the interactive mapping for these?
    a. How were they determined etc.
        i. Forgive me, I have missed several of the latest meetings.
2) Recharge was touched upon. I did not see or hear discussion regarding banking of In-Leu or recharged water within the basin.
    a. I am sure it would be a minimal amount but may think about using within the water budget?
        i. Is banking being addressed in the GSP?

Thanks;

Mathew E. Jones
T&P Farms / T&P Farms Huller & Sheller
Regulatory Operations Manager
O: (530) 476-3137
C: (530) 712-1227

From: Ben King [mailto:bking@pacgoldag.com]
Sent: Saturday, February 27, 2021 2:58 PM
To: Mary Fahey <mfahey@countyofcolusa.com>
Cc: Ben King <bking@pacgoldag.com>
Subject: February 17 CGA Presentatin

Hi Mary,

I wanted to point out that there are two different versions of the Presentation for the 2/17/21 on the CGA Website

If I look at the Meetings Link:

https://colusagroundwater.org/mdocs-posts/2021_02_17-cga-board-special-meeting-presentation/

There is a version without maps

If I look at the Presentations link:

https://colusagroundwater.org/mdocs-posts/2021_02_17-cga-board-special-meeting-presentation-ma/

The Presentation includes maps under Areas of Interests. The link in the Agenda also includes this version. Perhaps this was part of the Agenda Materials that was updated at the Meeting?

Best Regards,

Ben

From: Ben King <bking@pacgoldag.com>
Sent: Sunday, February 28, 2021 4:58 PM
To: Ceppos, David M <dceppos@csus.edu>
Cc: Mary Fahey <mfahey@countyofcolusa.com>; Davison, Brandon@DWR <Brandon.Davison@water.ca.gov>; Ben King <bking@pacgoldag.com>; dkalfsbeeksmith@countyofcolusa.org
Subject: Groundwater Arsenic Contamination Issues Raised by Springhorn Follow Up

HI Dave,

I was finally able to get access to Stephen Springhorn's paper on the Sutter Buttes Rampart. I want to make sure that Mr. Clark and Mr. Loy are aware of his recommendations and concerns as they draft the Basin Setting for the Colusa Basin especially in light of the work highlighted in a recent USGS Paper on arsenic contamination.

Stephen Springhorn had two relevant points concerning arsenic contamination:

> (I)Under **Future Work** – ".. additional data collection regarding " Elevated arsenic concentrations in groundwater related to the Sutter Buttes Rampart material".
> (II) In 6.1 – " Data analyses suggest there is a connection between elevated arsenic concentrations in groundwater and the presence of the Sutter Buttes Rampart volcaniclastic material .."

In the USGS Paper 1358 " Water Quality in Basin-Fill Aquifers of the Southwestern United States: Arizona, California, Colorado, Nevada, New Mexico and Utah, 1993-2009. The causal connection between volcaniclastic material and arsenic contamination of groundwater is established for water with pH greater than 8 and under anoxic conditions.

> See Page 54 " The interaction of metal oxides, particularly iron oxide, is one of the most important processes by which groundwater can be enriched or depleted in arsenic.....**If the PH is greater than 8, arsenic tends to desorb from the iron oxides and dissolves into the groundwater. Under anoxic conditions, iron oxides dissolve and release iron and arsenic into the groundwater regardless of pH"**

In the area of the Sutter Buttes Rampart, potentially via the Willows Fault and south of the Sutter Buttes we experience either very high pH observations or connate anoxic seawater. See the attached table included in the Sutter-Yuba Investigations report showing TDS levels as high as 10,000 in the Sutter Basin as of 1949. Additionally, see the attached table in the Curtin Paper which includes 137 well observations in his 1971 Paper. There are several observations of TDS above 5000 from Township 13 N southward and surprisingly in several shall wells also.

> Regarding the Willows Fault and potential for translocation of connate water leading to arsenic contamination as far north as Princeton - the USGS report mentions a situation in the Rio Grande where " The highest concentrations of arsenic in groundwater in the Middle Rio Grande Basin are associated with volcanic rocks in the northern part of the basin and **with fault zones through which deep, mineralized groundwater rises**."