UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



# SUSANVILLE-HONEY LAKE GEOTHERMAL RECONNAISSANCE SOUTHERN LASSEN COUNTY, CALIFORNIA

By
William F. Hardt, Franklin H. Olmsted,
and Frank W. Trainer



Prepared in cooperation with the
U.S. Bureau of Reclamation

ADMINISTRATIVE REPORT



Laguna Niguel, California
1975

## DISCLAIMER

# DISCLAIMER

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[1] All illustrations are at the end of the report. The page number given is that of the first principal reference to the illustration in the text.

The following table is appended for the convenience of readers who wish to convert units between English and metric systems.

Temperature

degrees Fahrenheit (°F) = [(9/5 x °C) + 32]

degrees Celsius (°C) = [(5/9)x (°F x 5/9)]

Length

3.28 feet = 1 metre

0.62 mile = 1 kilometre

1 foot = 0.3048 metre

1 mile = 1.609 kilometres

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## INTRODUCTION

As part of an appraisal of the nature and economic potential of the geothermal resource in the vicinity of Susanville and Honey Lake, the U.S. Bureau of Reclamation has been collecting geologic and hydrologic data, making resistivity surveys, obtaining thermal-infrared imagery, consulting with the U.S. Geological Survey, and drilling shallow temperature-gradient holes.

This report, prepared by the Geological Survey in cooperation with the Bureau of Reclamation, presents the results of a brief reconnaissance study of the geothermal resource in the Susanville-Honey Lake area using the available geologic and hydrologic data.

## Area Studied

The study area centers on an east-west alluvial embayment on the east flank of the Sierra Nevada in southern Lassen County, Calif. (fig. 1). The town of Susanville is at the northwest corner of this embayment, near the contact of basalt and alluvium. The major hot springs flow from alluvial deposits at Wendel and Amedee, near Honey Lake, about 25 miles east of Susanville, and that part of the area has thus been of primary interest for development of thermal water. There are several thermal water wells at Susanville. Development as near Susanville as possible is attractive for economic reasons. However, the area surrounding the hot springs at Wendel and Amedee has been designated a KGRA (Known Geothermal Resource Area), and two deep test holes have been drilled there by industry.

In developing the conceptual model for cold-and thermal-water circulation and discharge in the Susanville-Honey Lake area, it was necessary to encompass a larger study area than the alluvial embayment. Accordingly, the area north of Susanville and Honey Lake was also investigated briefly.

## Objectives of the Study

The purpose of this short-term reconnaissance was to (1) define and appraise the geothermal resource on the basis of the available data; (2) assist in planning a program of shallow test drilling for temperature information, scheduled for October 1975; and (3) develop concepts for use in planning more detailed future investigations.

## Acknowledgments

The writers gratefully acknowledge helpful discussions with Hibbard E. Richardson, Lyle T. Tomlin, and Gary A. Hollinger of the U.S. Bureau of Reclamation, Sacramento, and Robert Clawson of the California Department of Water Resources, Red Bluff.

## Methods of Investigation

The methods of study used were controlled by the stringent time limit, which permitted neither additonal field work nor the collection of new data.

The first step in the investigation was to collect and study all pertinent geologic, geophysical, hydrologic, and chemical data. Published and unpublished reports on the area were studied, as well as papers dealing with theory, methods of exploration and drilling, collection of data, and various methods of data analysis. Particular attention was given to water temperature, water chemistry, and the development of a conceptual model of thermal and non-thermal water mixing.

After cataloging all data an outline was developed to cover the objectives of the study. In writing the report the primary consideration was in fitting the information together and developing conceptual models of the Susanville-Honey Lake hydrothermal system. Because of the paucity of data, judgment based on hydrologic experience was utilized to complete the conceptual models. A designed field program, based on this reconnaissance, will be able to evaluate the validity of these models.

## Sources and Adequacy of Data

A detailed study was made of previous publications (see Selected References) and of geologic and hydrologic data. The most useful data and compilations were (1) drillers' logs of wells,(2) a gravity map, (3) a resistivity map, (4) selected electric logs of drill holes, (5) a geologic map showing faults, (6) geologic sections and stratigraphic columns, (7) water-quality analyses, (8) a water-level contour map, (9) temperature-gradient profiles in three wells in Susanville, and (10) water-temperature measurements in wells and springs.

These data had been collected and the compilations made by many workers over a considerable period. They are not of comparable accuracy, and much of the information needed to develop and test geologic and hydrologic hypothesis is not available. No conceptual model of the hydrothermal system had been developed.

## GEOTHERMAL ENVIRONMENT

The basic elements of a hydrothermal system are (1) a heat source, (2) a recharge mechanism, (3) a circulation mechanism, and (4) a discharge mechanism. Geothermal energy is natural heat derived from the earth's interior. In areas unaffected by local crustal heat sources or by convection, a typical geothermal gradient in the outer part of the crust is on the order of 1° C (Celsius) 100 feet of depth. At this gradient, the temperature at a depth of 10,000 feet (3 kilometers) below the land surface would be about 110° - 120° C. The heat of this depth cannot be extracted economically with present technology unless the temperature is considerably greater. However, geothermal gradients much greater than 1° C per 100 feet exist near areas of upward convection of hot water or near local crustal sources of heat. The hot water wells at Susanville and the hot springs at Wendel and Amedee are in such areas.

There are two phases of the problem of the origin of thermal water: the source of the water and the source of the heat. The water may be of meteoric, connate, or, usually to a minor degree, magmatic or juvenile origin. In most systems studied to date, the thermal waters are predominantly meteoric in origin. The source of heat may be (a) a body of intrusive magma or recently solidified igneous rock at depth in the crust; (b) extrusive igneous (volcanic) rocks young enough to retain their original heat; (c) the "normal" heat flow of the earth, which results in large part from the disintegration of radioactive elements; or (d) active faults on which movement generates heat.

Thermal waters in the Susanville-Honey Lake region are assumed to be predominantly meteoric in origin. Recharge to the aquifers is from precipitation and runoff which move downward to considerable depths in the rocks and unconsolidated deposits. Discharge is either from springs such as Wendel or Amedee, or from broad areas of evaporation such as Honey Lake. Thus, the water in the thermal reservoir moves slowly in response to recharge and discharge.

# REGIONAL SETTING

## Regional Geohydrology

The Susanville-Honey Lake area occupies a western embayment of the Great Basin physiographic province. To the north lies the Modoc Plateau, underlain by Tertiary and Quaternary volcanic rocks. To the southwest is the northern Sierra Nevada, in which the exposed rocks adjacent to the area of study are chiefly Mesozoic granitic rocks and overlying Tertiary volcanic rocks. Thermal springs are numerous in the region; they are associated with both volcanic rocks and faults.

The geology of this region is described in various reports; those pertinent to this geothermal reconnaissance include California Department of Water Resources, Bulletin 98, 1953; California Division of Mines and Geology, Bulletin 190, 1966 (Macdonald, 1966); geologic map of California, Westwood sheet (Lyndon and others, 1960) and Alturas sheet (Gay and Aune, 1958); and an unpublished report by Duffield and Fournier (1973). A brief geologic summary, largely extracted from the above reports, is included in this report. Figure 2 shows the geology of the region immediately north of the Susanville-Honey Lake area and the locations of representative stratigraphic and geologic sections in Willow Creek Valley and Secret Valley (fig. 3, 5) and Honey Lake Valley (fig. 4).

The Tertiary Period was marked by widespread volcanism and the pouring out of enormous lava floods and ash flows. Minor volcanism continued into the Pleistocene. Volcanic rocks older than 10 million years, according to calculations by A. H. Lachenbruch (1968), have long since cooled to the temperatures of other rocks, but the younger volcanic rocks of latest Tertiary and Quaternary age might be associated with shallow crustal sources of heat (Olmsted and others, 1975). According to Woods (1974), some geothermal activity is associated with geologically recent volcanic or fault activity as tectonic forces generate the heat. These relations will be of concern in development of a conceptual model of the geothermal system.

The Susanville-Honey Lake area is flanked by volcanic rocks (basalt) on the north and granitic rocks on the southwest (fig. 2, 6, 7). The Skedaddle and Amedee Mountains, to the northeast, are the remains of a large eroded volcano that has been truncated by the Amedee fault (between Amedee and Wendel in fig. 2). Shaffer Mountain, another volcano farther west, has not been greatly modified by faulting. North of Susanville the valley is flanked by a low basaltic plateau modified by block faulting. The upland west of Susanville, also underlain by volcanic rocks, is a transition zone bewteen the Basin and Range province to the east and the Cascade Range to the west.

Earlier water-resources investigations (California Dept. Water Resources, 1963; Glancy and Rush, 1968; Rush and Glancy, 1967), have shown gross areal relationships in the shallow ground-water flow system in the Susanville-Honey Lake area and vicinity. As summarized in figure 8, the shallow ground water flows into the Honey Lake Valley from the highlands to the north, west, and south, and then eastward toward Pyramid Lake. The shallow ground water in springs and wells in the basalt and in the unconsolidated deposits is typically cold.

The rocks exposed north of the Susanville-Honey Lake area are Pliocene and Pleistocene basalt. Study of the stratigraphic section in Honey Lake Valley (fig. 4) suggests that these rocks may represent the deepest aquifer for extensive movement of ground water in the Honey Lake area. The basalt is estimated to be 4,000 feet thick; it interfingers with the generally poorly permeable lake deposits. The lake deposits, possibly 5,000 feet thick (California Dept. Water Resources, 1963, p. 210), may act as a hydrologic barrier to the movement of ground water, causing upward movement of ground water in the area of faults inferred by earlier workers to cut the valley floow near Amedee and near Litchfield (see fig. 2, 7). Volcanic or granitic rocks of unknown hydrologic characteristics lie beneath the lake beds.

The pattern of ground-water movement in the Susanville-Honey Lake area is not known in sufficient detail to permit an accurate appraisal of the geothermal resource. Movement of cold ground water through irregular flow paths in the basalt near recharge areas could mask deeper thermal anomalies. Temperatures and temperature gradients in shallow holes might therefore fail to reveal the presence of thermal reservoirs beneath the zone of shallow ground-water flow.

The regional heat flow in the Susanville-Honey Lake area is not known. Measurements in the region to the south (Sass and others, 1971) suggest that the heat flow in the Susanville-Honey Lake area is about 2 HFU (heat-flow units, microcalories per square centimetre per second). Nor is the source of the heat in the thermal waters of the valley known. Of potential interest to this study are the Pliocene and Pleistocene basalts at the Wendel-Amedee area, the volcanic-granitic association at Susanville, and the series of North-and west-trending faults in the valley. According to previous investigators, the thermal areas appear to be structurally controlled by the faults, as is suggested by the occurrence of thermal waters at Susanville and at Amedee and Wendel Hot Springs. It is possible that the heat carried by the thermal waters is brought from considerable depth by deeply circulating water, or that it is derived from shallow heat sources such as volcanic vents that may be present beneath the basin fill of sediment.

## CONCEPTUAL MODELS OF THE GEOTHERMAL SYSTEM

From the evidence described in the section "Regional Geohydrology," it is inferred that the Susanville-Honey Lake geothermal systems are related to the circulation of meteoric water in the volcanic and granitic rocks associated with faults. Chemical characteristics of the thermal waters indicate that the systems are low temperature (probably mostly 150°C or less). Sources of heat for the circulating waters are postulated in two conceptual models.

One model consists of a hydrothermal system in an area of normal regional heat flow with no local heat source in the upper crust (fig. 9, A). The other model consists of a local heat source in the upper crust superimposed on the regional heat flow (fig. 9, B). The model lacking a local heat source requires the deeper circulation for the water to attain a given temperature.

Olmsted and others (1975, p. 51) give an example of the depths of circulation required, for the water to attain given temperatures, in the absence of a local heat source in the upper part of the crust. If the regional heat flow is 2 HFU, average thermal conductivity of the rock is $6.0 \times 10^{-3}$ cal $cm^{-1}$ $s^{-1}$ $°C^{-1}$ (representative of granite), and the mean annual temperature at the land surface is 10°C, water would have to circulate to a depth of 4.5 km (about 15,000 ft) to attain a temperature of 160°C, and to a depth of 5.7 km (about 19,000 ft) to attain a temperature of 200°C.

In the model having a local source of heat the water need not circulate to such great depths to attain a comparable temperature. Moreover, small lateral extent of ground-water circulation and a nearby source of recharge are somewhat more plausible with a local heat source than where such a source is absent. However, deep-seated faults can short-circuit the movement of ground water and permit deep circulation of meteoric water within small lateral distance where local heat sources are absent. The conceptual model adopted on the basis of meager data for the Susanville-Honey Lake area assumes (1) lateral ground-water movement of not more than 30 miles, and (2) local heat sources. The nature of such heat sources can only be suggested speculatively without additional information. Resistivity data (U.S. Bureau of Reclamation, oral commun., 1975) suggest the possible presence of vent-filling volcanic rocks beneath the alluvium of the hot-spring areas. A resistivity low at Susanville indicates a possible thermal anomaly; hydrothermal discharge there appears to be controlled by a fault along the western edge of the city.

Olmsted and others (1975) postulate two conceptual models of discharge for geothermal systems in nearby Nevada (fig. 10). One system has a nonleaky discharge conduit, and the other system has a leaky discharge conduit. According to Olmsted and others (1975, p. 53-54, 57)...[In] the nonleaky system...the vertical or nearly vertical conduit system is isolated hydraulically from the adjacent deposits or rocks by impermeable walls formed by minerals precipitated from the thermal fluid, or the conduit system may consist of fractures in impermeable rocks which are isolated from other fracture systems. All or nearly all the rising water therefore discharges at the land surface as springflow---Heat is discharged laterally from the conduit system by conduction through the conduit walls.

Relatively large thermal gradients are maintained through the conductive zone. The surrounding nonthermal ground water is heated, and the heat may be transported laterally by convection in the direction of the local hydraulic gradients. If the upper part of the conduit system is surrounded by unsaturated rocks, heat flow away from the system is almost entirely by conduction. The thermal area surrounding the conduit system, where conductive heat flow through near-surface materials is above 'normal,' is of the order of 0.5-5 $km^2$ on the basis of model studies by M. L. Sorey (oral commun., 1974)...

"...[In the] leaky discharge conduit [system]...some of the rising thermal water leaks laterally into aquifers. The amount of leakage may vary from a small proportion of the upward flow from the thermal reservoir to all the flow, so that no water discharges as liquid at the land surface. Where the leakage is small, little heat is transported laterally from the conduit system by convection, and the near-surface distribution of temperature is similar to that in the nonleaky-conduit system. Where the leakage is large,...the near-surface distribution of temperature is modified greatly because of lateral convective heat transport by the movement of thermal water through the aquifers intersected by the conduit system. As a result, the extent of the thermal area defined by above-'normal' temperatures and thermal gradients in the near-surface materials is much greater than that in the nonleaky system."

Study of the Susanville-Honey Lake data in light of these two conceptual models suggests that discharge of thermal water at Wendel and Amedee Springs is similar to that postulated for a nonleaky system, but that discharge of Susanville and in much of the remainder of the area in which thermal water has been found in wells is of the leaky type.

# GEOTHERMAL RESOURCE IN SUSANVILLE-HONEY LAKE AREA

## Description of the Thermal Areas

### City of Susanville

Although there are no hot springs in Susanville, at least 5 wells in the southwestern part of the city produce hot water. All the wells are within a small area in secs. 5 and 6, T. 29 N., R. 12 E., and are adjacent to a possible extension of the Honey Lake fault (fig. 2). No warm water has been reported north of the Susan River.

Temperature surveys of three of the wells are shown in figure 11. All three temperature profiles show the effects of both upward and lateral convection of thermal water. All three profiles also indicate an upper zone, ranging in thickness from about 50 feet in profile 1 to nearly 300 feet in profile 3, in which the gradients are relatively large and are probably conductive.

Other thermal wells in use include those of the Church of Latter Day Saints, which uses 49°C water to heat buildings; of Miller's Custom Works, which uses 40°C water for cleaning equipment; and of Sierra Pacific Industries (26°C water). The cooler water in the last well, which is closer to the city center than the other wells, indicates either a greater admixture of cool water (from the Susan River) or more cooling of the thermal water as it moves laterlally away from the fault source.

Table 1 shows the water quality of the Roosevelt swimming pool and the church well. This water quality is different from that of the thermal waters at Wendel and Amedee, suggesting different sources, different circulation patterns and mixing, or both.

Table 1.--Quality of water from selected wells and springs in Susanville-Honey Lake Area (data from files of California Department of Water Resources).

| Sample Number | Location | Name | Date Sampled (mo/dy/yr) | Producing Depth (m) | Altitude (m) | Water Temperature (°C) | pH | Conductivity (μmhos/cm) | Discharge (l min) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | NE/NE Sec.6 T.29N., R. 12E., M.D. | Roosevelt Swimming Pool | 7/18/73 | 90 (?) | 1295 | 35.8 | 8.01 | 0.254 | Pumped |
| 2 | SE/NE Sec. 6 T. 29N., R. 12E., M.D. | Latter Day Saints Church | 7/18/73 | 169-181 | 1263 | 48.8 | 7.87 | 1.07 | 800 Pumped |
| 3 | SW/SE Sec.23 T. 29N., R. 15E., M.D. | Wendel Hot Springs | 7/17/73 | spring | 1231 | 95.6 | 8.38 | 3.34 | 1200 |
| 4 | NE/SW Sec.30 T. 29N., R.16E., M.D. | Southern Pacific Railroad | 7/17/73 | 93 | 1223 | 28.2 | 8.33 | 0.332 | 300 Pumped |
| 5 | NW/NE Sec.8 T. 28N., R.16E., M.D. | Amedee Hot Springs | 7/17/73 | spring | 1219 | 95.1 | 8.43 | 2.86 | 500 |

Chemical Constituents (in mg/l)

| Sample Number | Cations | | | | | | | | Anions | | | | Others | | Calculated Dissolved Solids |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Li | Na | K | Rb | Mg | Ca | Zn | F | Cl | $HCO_3$ | $CO_3$ | $SO_4$ | $SiO_2$ | B | |
| 1 | <0.01 | 20 | 3.8 | < 0.01 | 3.4 | 19 | 0.043 | < 0.1 | 2.0 | 120 | 1 | 11 | 53 | < 0.02 | 233 |
| 2 | 0.05 | 140 | 4.6 | 0.02 | 1.6 | 24 | 0.009 | 1.2 | 64 | 68 | 1 | 190 | 62 | 1.4 | 558 |
| 3 | 0.12 | 280 | 7.5 | 0.04 | < 0.1 | 18 | 0.015 | 4.1 | 190 | 50 | 1 | 360 | 120 | 5.5 | 1040 |
| 4 | 0.01 | 58 | 8.0 | 0.01 | 2.2 | 6.0 | < 0.005 | 0.2 | 17 | 112 | 1 | 32 | 42 | 0.22 | 279 |
| 5 | 0.08 | 250 | 5.5 | 0.02 | < 0.1 | 14 | < 0.005 | 4.4 | 160 | 44 | 2 | 300 | 95 | 4.0 | 879 |

Trace Constituents Below Detection:

Ca <0.1, Mn <0.01, Fe <0.06, Cd < 0.01, Co < 0.05, Cu < 0.02, Ni < 0.04, Pb < 0.1

## Wendel and Amedee Springs

Wendel, (formerly Shaffer) and Amedee Hot Springs are described by Waring (1915, p. 124-127). Waring's discussion is as follows:

In Honey Lake valley there are two large groups of hot springs—one, the more interesting, near Hot Springs railroad station and the other near Amedee. At the former locality, near the northeastern side of Honey Lake, a belt of calcareous tufa extends from the base of steep slopes that border the valley near the railroad station southwestward for nearly half a mile. The continuity of the surface exposure of the material is then broken, but the course of the deposit is marked for two-thirds of a mile farther by prominent crags and knolls of the material that rise in meadow and salt-grass land that extends to the lake. One of these crags is shown in Plate VIII, *A*. Seepage springs rise at several points along the middle part of this tufa belt, but the springs of chief interest issue beyond its most lakeward outcrop. They are not known locally by a definite name, but as they were referred to in 1882 by Russell as Shaffer Hot Springs, this name is here used.

The principal spring rises with vigorous ebullition in a pool about 10 yards in diameter and 1 or 2 feet deep. The water was formerly thrown up to a height of 3 or 4 feet, but this action has been partially stopped by stones that have been cast into the pool. A temperature several degrees above boiling has been claimed for this spring, but 204°, near the center of the pool, was the highest temperature recorded. This is the same temperature at which water boiled in a bucket over a fire near the spring and is practically the calculated boiling point for this elevation (3,975 feet). A bathhouse that extended over a part of the pool was in 1909 used as a vapor bath. In 1882 Russell[1] estimated the flow of this spring to be 100 cubic feet a minute (748 gallons a minute), but in September, 1909, the average of three float measurements indicated a discharge of only about 175 gallons a minute. It does not seem probable that this great difference is due to error in measurement, and it is believed to show that the flow has actually decreased, possibly because of the partial choking of the vent with stones. Two other hot springs that discharge about 65 and 10 gallons a minute, respectively, and 6 or more hot pools that have no surface outflow, are formed in the nearly level salt-grass area in a distance of about 125 yards southwest of the main spring.

In his monograph on Lake Lahontan[2] Russell says of these springs and the associated tufa:

> This spring occurs at the southern end of a long row of tufa crags, fully 50 feet high and somewhat greater in breadth, a few of which still have small springs issuing from their bases. The tufa at the base of the crags, and forming the nucleus of the deposit, is amorphous, but is coated with a heavy deposit of the dendritic variety. * * * The former was a direct precipitate from spring water, but the latter was plainly deposited from the former lake. The evidence is such as to lead to the conclusion that this spring was fully as copious during the existence of Lake Lahontan as now, and that its point of discharge was crowded southward along a fissure as its former outlets became filled with calcareous tufa deposited from its own waters.

Russell also gives an analysis of the water, which is here reproduced, together with analyses that were made of the spring and lake waters in 1909. The analyses show that the spring water is a primary saline solution containing a large proportion of silica. The comparatively small amounts of calcium and carbonate present are of interest with respect to the large tufa crags, but calcium carbonate is easily formed and precipitated, so that large amounts are not necessarily present for the production of prominent deposits. The lake water is characterized by primary alkalinity as well as primary salinity.

[1] Russell, I. C., Geological history of Lake Lahontan: U. S. Geol. Survey Mon. 11, p. 51, 1885.
[2] Lake Lahontan is the name that has been given to a body of water that occupied Honey Lake Valley and adjacent valleys during early Quaternary time.

[Constituents are in parts per million.]

| | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| Properties of reaction: | | | | | | |
| Primary salinity | | 93 | .................. | | | 55 |
| Secondary salinity | | 0 | .................. | | | 0 |
| Tertiary salinity | | 0 | .................. | | | 0 |
| Primary alkalinity | | 2 | .................. | | | 39 |
| Secondary alkalinity | | 5 | .................. | | | 6 |
| Tertiary alkalinity | | 31 | .................. | | (?) | |
| **Constituents.** | **By weight.** | **Reacting values.** | **By weight.** | **Reacting values.** | **By weight.** | **Reacting values.** |
| Sodium (Na) | 304 | 13.22 | .......... | .......... | 622 | 27.04 |
| Potassium (K) | 9.4 | .24 | .......... | .......... | | |
| Calcium (Ca) | 12 | .60 | .......... | .......... | 21 | 1.05 |
| Magnesium (Mg) | .4 | .03 | .......... | .......... | 7.9 | .65 |
| Sulphate ($SO_4$) | 349 | 7.27 | 353 | 7.32 | 264 | 5.50 |
| Chloride (Cl) | 207 | 5.84 | 203 | 5.73 | 305 | 10.29 |
| Carbonate ($CO_3$) | .......... | .......... | .......... | .......... | 383 | 12.78 |
| Metaborate ($BO_2$) | .......... | .......... | Trace. | Trace. | .......... | .......... |
| Silica ($SiO_2$) | 131 | 4.34 | 120 | 3.98 | .......... | .......... |
| | 1,012.8 | .......... | 676 | .......... | 1,602.9 | .......... |
| Carbon dioxide ($CO_2$) | .......... | .......... | .......... | .......... | 0 | .00 |

1. Main spring, Shaffer Hot Springs. Analyst, F. W. Clarke (1883). Authority, U. S. Geol. Survey Bull. 9.
2. Main spring, Shaffer Hot Springs. Analyst, G. E. Colby (1909). Authority, owner of springs.
3. Honey Lake. Analyst and authority, F. M. Eaton (1909). Sample collected 75 yards from northeast shore, where water was 18 inches deep.

Dana[1] has made a close examination of the calcareous tufa deposited in the basin of Lake Lahontan. Three varieties are recognized, which differ chiefly in physical characteristics. The variety at Shaffer Hot Springs, which assumes mushroom shapes, is much the commonest and is known as dendritic tufa. An analysis of the material is here reproduced, because, though not strictly a hot spring deposit, the crags near Shaffer Hot Springs are evidently closely related to the presence of the hot water.

*Analysis of dendritic tufa from basin of Lake Lahontan.*

[Analyst, D. O. Allen (1882 ?). Authority, U. S. Geol. Survey Mon. 11, p. 203.]

| | |
|---|---|
| Insoluble residue | 5.06 |
| Iron and alumina ($Fe_2O_3+Al_2O_3$) | 1.29 |
| Calcium oxide (CaO) | 49.14 |
| Magnesium oxide (MgO) | 1.99 |
| Chlorine (Cl) | Trace. |
| Sulphate ($SO_4$) | Trace. |
| Phosphate ($P_2O_5$) | Trace. |
| Carbon dioxide ($CO_2$) | 40.31 |
| Water ($H_2O$) | 2.01 |
| | 99.80 |

[1] Dana, E. S., A crystallographic study of the thinolite of Lake Lahontan: U. S. Geol. Survey Bull. 12, 1884.

## AMEDEE HOT SPRINGS (LASSEN 17).

The second group of hot springs in Honey Lake Valley is about 5 miles southeast of Shaffer Hot Springs, near Amedee depot. The land here is alluvial and slopes very gently westward toward Honey Lake. Scalding water forms several groups of shallow pools, mainly at six places in a belt about 600 yards long that trends nearly southward, but one-third of a mile S. 30° W. (magnetic) from the southernmost of these main groups another hot spring forms a pool in salt-grass land, and hot water probably rises at other places still farther toward the lake. Temperatures of 172° to 204° (practically the boiling point at this elevation, 4,000 feet) were noted in the several springs, and the total discharge of hot water as measured by the flow of six run-off streams is about 700 gallons a minute.

In 1909 the springs had not been improved to great extent, but there was a small bathhouse beside the railroad, near one of the largest groups of springs. At the southernmost of the main groups there was also an old bathhouse, and water from one of the northernmost springs was used in preparing sheep dip. At the Amedee Hotel a shallow well 80 yards east of the nearest springs supplied water at a temperature of 134° for kitchen use.

There are no prominent deposits of tufa at Amedee, such as there are near Shaffer Hot Springs, but near the southernmost of the main groups tufa appears over a small area. The hottest spring rises from this material. The following analysis of the water from this spring shows that it is a primary saline water almost identical in character with that of the Shaffer spring but of slightly less concentration.

*Analysis of water from Amedee Hot Springs, Lassen County, Cal.*[a]

[Analyst and authority, F. M. Eaton (1909). Constituents are in parts per million.]

| | |
|---|---|
| Temperature | 96° C. (204° F.) |
| Properties of reaction: | |
| Primary salinity | 91 |
| Secondary salinity | 0 |
| Tertiary salinity | 0 |
| Primary alkalinity | 1 |
| Secondary alkalinity | 8 |
| Tertiary alkalinity | 28 |

| Constituents. | By weight. | Reacting values. |
|---|---|---|
| Sodium (Na) | 232 | 10.18 |
| Potassium (K) | 4.9 | .13 |
| Calcium (Ca) | 18 | .90 |
| Magnesium (Mg) | Trace. | Trace. |
| Iron (Fe)<br>Aluminum (Al) | 1.8 | .06 |
| Sulphate ($SO_4$) | 269 | 5.60 |
| Chloride (Cl) | 164 | 4.62 |
| Carbonate ($CO_3$) | 27 | .91 |
| Silica ($SiO_2$) | 94 | 3.12 |
| | 810.7 | ........ |
| Carbon dioxide ($CO_2$) | Present. | Present. |

[a] Spring 180 yards southwest of Amedee depot.

Table 1 and Waring (1915) present water analyses for these springs that cover a span of 60 years. The water quality has not changed greatly during this time.

The flow of Amedee Hot Spring was 700 gal/min (gallons per minute) in 1909 (Waring, 1915) and is about the same today. The flow of Wendel Hot Spring was reported by Stearns and others (1937) and Waring (1965) to be about 250 gal/min. Waring (1915) reported that it measured 175 gal/min in 1909. The flow of 748 gal/min in 1882 (reported by Russell and cited in the foregoing quotation from Waring), if correct, may reflect changes in the points of discharge owing to sealing by calcareous tufa. If the discharge conduits have become partly plugged, the total thermal discharge may now be mixing with shallower cold water over a larger area than formerly.

The convective heat discharge by springflow is estimated to be $1.3 \times 10^6$ cal $s^{-1}$ for Wendel and $3.8 \times 10^6$ cal $s^{-1}$ for Amedee, on the basis of calculations that assume an average discharge temperature of 100°C., a mean annual air temperature of 10°C., and flow of 250 gal/min for Wendel Hot Spring and 700 gal/min for Amedee Hot Spring.

In 1962 Magma Power and Associates drilled one well in sec. 23, T. 29 N., R. 15 E., near Wendel Hot Spring, to a depth of 630 feet, and measured a maximum temperature of 64°C. Three wells were drilled in secs. 5 and 8, T. 28 N., R 16 E., near Amedee Hot Spring; the deepest hole, to 1,116 feet, had a maximum temperature of 107°C.

Gulf Oil Co. drilled two geothermal wells in 1973: one in sec. 5, T. 28 N., R. 16 E., to a depth of 5,034 feet, and one in sec. 25, T. 29 N., R. 15 E., to a depth of 5,056 feet. Data from these holes have not been released. On August 18, 1975, the well in sec. 25 was flowing 5-10 gal/min from a broken valve. The water temperature was estimated to be 27°-32°C., with fair water quality except for a "sulfur" taste.

## Geophysical Data

### Bouguer Gravity Map

A Bouguer gravity survey of the Susanville-Honey Lake area was made for the California Department of Water Resources by J. I. Gimlett (1960) (fig. 12) to determine the configuration of the pre-Tertiary rocks that form the boundaries of the basin, and to estimate the thickness of fill. Figure 12 suggests a northwest-trending basin having the deepest part beneath Honey Lake and much shallower fill in the northwestern part, east of Susanville. According to an estimate by the California Department of Water Resources (1963), the maximum thickness of volcanic rock and sedimentary rocks beneath Honey Lake is about 5,000 feet.

The gravity data are not sufficiently detailed to indicate buried traces of faults or the location of less dense thermal fluids in the basin-filling rocks and deposits.

## Resistivity Map

A surface resistivity survey of the Susanville-Honey Lake area was completed by the Bureau of Reclamation in 1975; the results are shown in figure 13. The low resistivities at Susanville and near Wendel and Amedee Hot Springs correlate well with thermal anomalies at those localities; the effect of local geothermal anomalies evidently is to introduce a local decrease in resistivity. Of particular interest for future exploration are the areas between Leavitt and Litchfield, along the north side of the basin, and east of Buntingville, where the map shows areas of low resistivity.

The lines of resistivity survey are not shown on the map, so it is difficult to assess the significance of the low resistivity anomalies in relation to blank areas on the map. The resistivity survey looks encouraging for locating thermal anomalies and should be expanded to cover the valley if coverage is now incomplete.

The following discussion, from Meidav and Furgerson (1971), points out some of the interrelations among temperature, salinity, and resistivity in hydrothermal reservoirs and illustrate the use of these data in the interpretation of geothermal conditions.

"Where an outstanding geothermal reservoir does exist, the electrical resistivity across it usually varies by a factor of at least 3-10 (Studt, 1958; Hayakawa, 1966, Breusse, 1964). It also turns out, that because of convective circulation, the concentrating effect due to boiling off from the geothermal reservoir, and the higher dissolving power of the heated reservoir water, the salinity of the fluids within the body of the geothermal reservoir is greater than outside the reservoir. Thus, the salinity and temperature effects are often working together to enhance the electrical conductivity of the geothermal reservoir and thus sharpen the electrical resistivity anomaly over a geothermal reservoir. The high contrast in resistivity between the reservoir rock and the surrounding rock is particularly notable in volcanic terrain. In such areas, the resistivity within the geothermal reservoir usually falls to 10 ohm-meters or less, regardless of how high the resistivity outside the reservoir area. In some exceptional cases, such as in the present study, where the regional resistivity values are quite low to begin with, because of the preponderance of clay and shale within the geological section, the resistivity change across a geothermal area turns out to be less outstanding. Because clay and shale possess a finite electrical conductivity of their own, they tend to attenuate the amplitude of the conductivity change due to temperature".

## Indicators of Temperature

Measurements in some wells and springs in the Susanville-Honey Lake area indicate temperatures as high as the boiling point or slightly higher. Temperatures at depth in the subsurface are not known, and no heat-flow studies are known to have been made in the area. Water-quality data representing the period 1957-74, tabulated by the California Department of Water Resources, were used to estimate subsurface temperatures. Study of the chemical analyses suggests possible reservoir temperatures of 150°C or more, but problems introduced by rock type and by methods of sampling and analysis lend considerable uncertainty to these estimates.

### Measured Water Temperatures in Wells and Springs

Figure 14 shows the distribution of temperatures of water discharged from wells selected for measurement. The temperatures are rounded to the nearest 1°C, represent water from different depths from well to well, and therefore provide only a crude indication of the presence and extent of deeper thermal anomalies. At many places, the temperatures probably are lowered by admixture of shallow cold water with the deeper thermal water as well as by upward conductive heat loss.

Temperatures appear to be a few degrees above normal in an elongated east-west area between Susanville and Wendel-Amedee, along the north side of the valley. The area includes a less extensive resistivity low and appears to be favorable for geothermal exploration.

The near-surface thermal anomaly at Susanville is of relatively small extent and coincides with the resistivity low. The Wendel-Amedee thermal anomaly is of greater extent and also conforms well with the resistivity low, (compare figs. 13 and 14.)

The correlation of higher temperature with lower resistivity is less apparent east of Buntingville than it is in the other areas just described (figs. 13, 14). More work is needed to resolve this apparent discrepancy.

## Inferred Reservoir Temperatures

Reservoir temperatures were estimated using three geochemical methods: the silica geothermometer, the Na-K-Ca geothermometer, and a mixing model.

The silica geothermometer (Fournier and Rowe, 1966), based on the silica content of the water, is inferred to show the temperature at which the water was last in equilibrium with quartz. If the silica content of the water is assumed to have been derived entirely from quartz and if the water is assumed to have flowed from the reservoir to the well or spring without significant loss or gain in silica content, this equilibration temperature provides an estimate of the minimum reservoir temperature. Application of this method to the Susanville-Honey Lake area, using chemical analyses for samples from water wells and springs in the files of the California Department of Water Resources, suggests temperatures near 100°C, with a rough geographic zonation. Inferred temperatures in the southern part of the area commonly fall in the range 80°-100°C. In a central zone that is elongated from west to east and extends from Susanville to Wendel and Amedee (see fig. 2 for locations of localities named) most inferred temperatures are in the range 100°-110°C. In a northerly zone extending from near Litchfield to the vicinity of Leavitt the inferred temperatures are mostly between 110° and 120°C.

This pattern of temperatures gives qualitative confirmation to other data, considered in earlier sections of this report, which suggest a region of higher subsurface temperatures in the northern part of the area, between Amedee and Susanville. For two reasons the silica data do not warrant a more precise estimate of the temperatures. (1) In concentrations near or higher than those reported in many of these analyses, silica tends to precipitate from solution unless the samples are treated at the time of collection to prevent precipitation. There is no indication in the data that these samples were treated; and because they were collected many years ago, and by various workers, it is a fair assumption that they were not. (2) Many of the thermal waters in this area are reasonably explained as mixtures of hot and cold waters. Such dilution can be expected to result in lower silica contents and inferred temperatures than those representative of the original hot waters. The silica temperatures derived from the available analyses are therefore minimum estimates.

The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) provides an estimate of reservoir temperature based on the concentrations of sodium, potassium, and calcium in the water. Computations using the water analyses from the Susanville-Honey Lake area yield temperature estimates that range from about 100°C to more than 200°C. However, the areal pattern of values differs markedly from that for the silica temperatures. The lowest values, commonly less than 150°C, are at the eastern and western ends of the area, and the highest values in the central part; many of the higher values are in the south-central part of the area, and many intermediate values are in the north-central part where other evidence has suggested that reservoir temperatures may be relatively high. Temperature values inferred by use of this geothermometer diverge markedly from those from the silica geothermometer. This tendency is most conspicuous at numerous places where several silica temperatures are similar to one another whereas the corresponding cation temperatures are very different from one another. The silica estimates are believed to be more nearly representative of the reservoir temperatures than the cation estimates. The validity of the cation estimates may be affected by the widespread occurrence in this area of basalt, whose mineral composition does not favor equilibrium dissolution of all three cations on which this method depends.

A mixing model described by Fournier and Truesdell (1974) can be used, under favorable conditions, to estimate the original temperature of the hot water and the fraction of admixed cold water by using the temperatures and silica contents of the thermal spring or well water and of typical nonthermal ground water in the region.

Table 2 shows mixing-model data and calculated values for 10 selected wells and springs. (Approximate locations of these wells and springs are shown on figure 15.) Calculations for Amedee Spring and for well 29N/16E-30L1 were made for each of two different samples. The calculations for the Wendel-Amedee thermal area yield estimated reservoir temperatures in the range 153°-183°C, and suggest that the observed thermal water contains 41 to 50 percent admixed cold water. In the Susanville area, temperature estimates are 155° to 208°C, with a higher proportion of admixed cold water. The calculations were based on the assumptions of 10°C as the average temperature of the cold water on using 10° C. (average air temperature at Susanville) and of an $SiO_2$ content of 36 mg/l (from Bagwell Spring at Susanville) as representative of $SiO_2$ in the non-thermal water.

TABLE 2.--Selected springs and wells used in mixing model of cold and thermal waters[1]

| Well number or spring name | Date of water sample | Temperature (°C.) | $SiO_2$ (mg/l) | Estimated reservoir temperature (°C.) | Cold water fraction (percent) |
|---|---|---|---|---|---|
| Amedee Spring (28N/16E-8B1) | 1909 | 96 | 94 | 153 | 42 |
| | 1971 | 97 | 96 | 156 | 41 |
| 28N/17E-20J1 | 1956 | 27 | 39 | 112 | 83 |
| Roosevelt swimming pool (29N/12E-5D1) | 1974 | 39 | 59 | 165 | 81 |
| Latter Day Saints church well (29N/12E-5) | 1973 | 49 | 62 | 155 | 74 |
| 29N/15E-16G1 | 1958 | 27 | 54 | 193 | 91 |
| Wendel Spring (29N/15E-23K1) | 1971 | 97 | 117 | 183 | 50 |
| 29N/15E-24F1 | 1958 | 31 | 40 | 255 | 92 |
| Southern Pacific RR (29N/16E-30L1) | 1958 | 24 | 41 | 120 | 87 |
| | 1973 | 28 | 42 | 120 | 83 |
| 30N/12E-33N1 | 1958 | 17 | 45 | 208 | 96 |
| 30N/13E-31R1 | 1958 | 26 | 76 | 122 | 86 |

1. Background temperature of cold water before mixing is considered to be mean annual temperature at Susanville of 10°C.; silica content of cold water is 36 mg/l, derived from Bagwell Spring, 1½ miles northwest of Susanville. Data from files of California Department of Water Resources.

The temperature estimates based on the mixing model, represent parts of the area near Wendel, Amedee, and Susanville. The validity of the estimates cannot be determined until test holes have been drilled into the geothermal reservoir, but the estimates suggest that reservoir temperatures may be appreciably higher than the minimum values suggested by the silica geothermometer. Two sources of uncertainty about the significance of the temperatures suggested by the mixing model lie in (1) the fact that the thermal water that mixes with the near-surface cold water in this area may itself be a blend of waters, of many different temperatures, which have come from different depths along different flow paths; and (2) the degree to which the silica content of water from the Bagwell Spring represents that of the cold ground water in the area is not known.

From the foregoing discussion it is concluded that the silica geothermometer probably provides reliable minimum estimates of reservoir temperatures; that the cation-geothermometer estimates are not reliable; and that the mixing-model estimates suggest reservoir temperatures considerably higher than do the silica estimates. None of these estimates is based on adequate data, and the careful collection and analysis of water samples should be an integral part of any exploration and test-drilling program.

## CONCLUSIONS

The following conclusions have been drawn from this brief review of geothermal data from the Susanville-Honey Lake area.

The area is underlain by unconsolidated deposits. Thermal waters occur in these deposits but are believed to have come from underlying basalt and perhaps from deeper granitic rock.

The occurrence of the thermal waters discharged by springs near Wendel and Amedee, and probably that of the thermal well water at Susanville, is fault controlled. In this respect these hydrothermal systems resemble other hydrothermal systems in the northwestern part of the Basin and Range province.

The general flow pattern for shallow ground water in the area suggests that the recharge area for the hydrothermal systems is to the north or northwest and that it is within 25 miles of Honey Lake Valley. The nature of the flow paths, principally through basalt, is not known, but these paths probably are complex.

Conceptual models for the hydrothermal circulation systems are (1) deep circulation of waters along faults and other conduits in areas of normal temperature gradients; and (2) shallower circulation near shallow crustal sources of heat. The latter model is believed more likely, but present evidence is far from conclusive.

The nature of the postulated heat sources is not known. The occurrence of late Tertiary and Pleistocene volcanism in the area suggests the possibility that volcanic necks are sources of heat. Resistivity data suggest localization of hydrothermal flow near the surface, which is consistent with the presence of fault conduits.

Thermal wells at Susanville are concentrated within an area of a few square miles, and none is known to be north of the Susan River. The distribution of cold-water wells around the thermal area suggests that the thermal anomaly is of limited area, but the quantitative significance of mixing of the thermal and cold water is not known.

The surface flow of Wendel Springs at the main orifice appears to have decreased from 748 gal/min in 1882 to 250 gal/min in 1970. This decrease may reflect partial plugging of the spring orifices, accompanied by more diffuse discharge at the surface and increased subsurface discharge. The discharge of Amedee Spring, about 700 gal/min, has not changed significantly from 1909 to 1971. Estimated convective discharge of heat is $1.3 \times 10^6$ cal $s^{-1}$ for Wendel Hot Spring and $3.8 \times 10^6$ cal $s^{-1}$ for Amedee Hot Spring, assuming a discharge temperature of 100°C and an air temperature of 10°C.

Resistivity and other data suggest an elongated area of thermal-water discharge between the principal known hydrothermal features at Susanville and near Wendel and Amedee. However, the movement of cold ground water through shallow permeable alluvium appears partly to mask the temperature effects of thermal water moving upward from depth.

Estimated temperatures for the thermal water in the elongated area between Susanville to the west and Wendel and Amedee to the east, based on the silica content of the water, are in the range 100°-120°C. This appears to be a reasonable minimum estimate for the reservoir temperature. Estimates based on a mixing model suggest that the observed thermal waters contain large proportions of admixed shallow ground water and that the original temperature of the hot water may have been appreciably higher--possibly as high as 150° to 200°C. The uncertainties involved in all these estimates are such, however, that resampling and new chemical analyses are needed. The estimates now available should be used only in planning further investigations.

## PROPOSED PROGRAMS

The objectives of planning a geothermal exploration program should include (1) locating the extent and configuration of the thermal areas; (2) estimating the volume, temperature, and permeability of the reservoir; (3) determining the nature of the heat and water sources and of the circulation system; (4) analyzing the chemical composition of the produced fluid; and (5) predicting the long-term heat or energy potential. Investigations planned to attain these objectives could logically include both local and regional studies. Because test drilling by the Bureau of Reclamation is planned for the autumn of 1975, local studies are emphasized in the program discussed in the following pages.

## Drilling Program

The information now available indicates that the Susanville thermal anomaly is small, underlying an area of a few square miles. Deep-seated thermal water is believed to be rising along localized conduits--probably faults--and mixing with shallow cold water. A phased drilling program is desirable in order to determine the form and areal extent of the thermal anomaly with shallow holes before drilling deep holes.

Temperature and gradient measurements at depths on the order of 3 feet are quick and inexpensive, and in some areas have been useful in detecting anomalously warm spots. The ground temperature is strongly influenced, however, by near-surface effects, including insolation, topography, precipitation, and movement of ground water. If the area for shallow temperature measurements is selected carefully and the measurements are made within a short time span (no more than a few days), the extraneous effects just mentioned can be minimized. The shallow temperatures then provide a clue to the location of temperature anomalies caused by hydrothermal discharge into shallow aquifers. Improved siting of deeper (100-200 feet) test holes is thus facilitated.

Several shallow test holes (100-200 feet deep) have been tentatively planned for the Susanville area by the Bureau of Reclamation (L. T. Tomlin, oral commun., 1975). Approximate locations for these holes are shown on figure 15. Additional shallow holes are also suggested (see fig. 15) to define better the lateral extent of the anomaly and to provide additional water samples and temperature measurements.

If the results obtained from these shallow holes are favorable, one or more deeper holes (to perhaps 1,000 feet or deeper) would be desirable in an effort to define the geothermal reservoir characteristics needed to evaluate the potential of the reservoir for development. Two deep holes are tentatively suggested on figure 15: one near the apparent center of the thermal anomaly and one near the fault at the north side of the anomaly. The actual sites of such holes should be selected on the basis of data provided by the shallow holes.

Figure 15 also shows the locations of shallow holes tentatively planned by the Bureau of Reclamation for the area near Wendel and Amedee, and of shallow holes suggested here as a result of this study. Assuming favorable results from this shallow drilling, deep test holes would also be desirable. If data from two test holes drilled by Gulf Oil Company can be obtained, however, it may not be necessary to drill in the Wendell-Amedee area. The Gulf holes, in sec. 5, T. 28 N., R. 16 E. and in sec. 25, T. 29 N., R. 15 E., are reported to be more than 5,000 feet deep and to be located on opposite sides of the Litchfield fault.

Also shown on figure 15 are the tentative locations of test holes on both sides of the inferred trace of the Litchfield fault between Susanville and the Wendel-Amedee area, and south of the fault to the west of Honey Lake. Holes drilled west of Honey Lake would preferably be located over the resistivity anomaly in sec. 1, T. 29 N., R. 13 E.

Assuming the availability of data from the Gulf wells, the preferred priority for the shallow drilling, by areas, appears to be as follows:

1. Susanville area, because of the favorable location for development of any resource found;

2. area along Litchfield fault, because the data available suggest higher reservoir temperatures than those found elsewhere in Honey Lake Valley; and

3. west of Honey Lake.

Planning of any deep drilling would preferably be deferred until after the entire shallow-drilling program had been completed. It is quite possible that results of the shallow drilling would favor sites and priorities for deep holes that were quite different from those that can be suggested now.

## Studies Related to the Drilling Program

Temperature profiles should be measured in all test holes. Where practicable (and certainly in all deep holes), core samples should also be collected to permit measurement of thermal conductivity (which, with thermal gradient, makes possible the calculation of heat flow) and the hydrologic properties of the materials. Geophysical logs should be made in the boreholes, flow and head data should be obtained, and representative water samples collected for chemical analysis. The analyses are needed to provide reliable data for the geothermometers and data for later evaluation of potential problems in development of the geothermal resource. Careful sampling and field treatment of the water samples (Presser and Barnes, 1974) is needed to insure the usefulness of the data for geothermal interpretation. Constituents determined in the analysis of geothermal waters preferably include silica; the principal ions; selected minor constituents such as aresnic and boron; and the stable isotopes of hydrogen and oxygen, used in study of source of the water.

Along with these studies related to the test holes it would be desirable to expand the surface-resistivity surveys already made by the Bureau of Reclamation to cover areas southeast of Susanville, along the Honey Lake fault, and east of Standish. In addition, geologic mapping is needed to identify structural relationships and especially to map faults; and to search for young rhyolitic rocks.

## Regional Studies

If the first exploratory field studies in the Susanville-Honey Lake area indicate promising potential for development of the geothermal resource, regional investigations should be made an integral part of further studies in the area. It is important to bring regional relationships to bear on the local problem; and to use local relationships in regional exploration. For example, the regional heat flow is a fundamental parameter needed in the interpretation of local sources of heat; and studies beyond a given topographic basin may yield important information about recharge to a hydrothermal system and about the ground-water flow pattern. In the region surrounding the Susanville-Honey Lake area it is important to learn more about flow through the basalts. On the other hand, geologic, hydrologic, geophysical, and thermal relationships in the Susanville-Honey Lake area could prove invaluable if geothermal exploration were extended into adjacent regions such as the Modoc Plateau to the north.

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Figure 1.--Map of northern California showing location of Susanville-Honey Lake area (arrow), from California Dept. Water Resources, 1968, p. 3.

(California Dept. Water Resources, 1963, p. 208).
For location of area represented by section, see figure 2.

| Geologic age | Geologic formation | Stratigraphy | Approximate thickness in feet |
|---|---|---|---|
| Cenozoic, Quaternary, Recent | Sand deposits | Qs | 0-25 |
| Cenozoic, Quaternary, Recent | Lake deposits | Ql | 0-25 |
| Cenozoic, Quaternary, Recent | Basin deposits | Qb | 0-50 |
| Cenozoic, Quaternary, Recent | Intermediate alluvium | Qal | 0-100 |
| Cenozoic, Quaternary, Recent | Landslides | Qls | 0-50 |
| Cenozoic, Quaternary, Recent | Alluvial fans | Qf | 0-300 |
| Cenozoic, Quaternary, Pleistocene | Near-shore deposits | Qps | 0-400 |
| Cenozoic, Quaternary, Pleistocene | Lahontan Lake deposits | Qpl | 0-700 |
| Cenozoic, Quaternary, Pleistocene, Pleistocene volcanic rocks | Basalt | Qpvb | 50-500 |
| Cenozoic, Quaternary, Pleistocene, Pleistocene volcanic rocks | Pyroclastics | Qpvp | 0-200 |
| Cenozoic, Quaternary–Tertiary, Plio-Pleistocene, Plio-Pleistocene volcanic rocks | Basalt | TQvb | 4000 |
| Cenozoic, Quaternary–Tertiary, Plio-Pleistocene, Plio-Pleistocene volcanic rocks | Pyroclastic rocks | TQvp | ? |
| Cenozoic, Tertiary, Pliocene | Pliocene lake deposits | Tpl | 0-5000 |
| Cenozoic, Tertiary, Pliocene | Pliocene pyroclastic rocks | Tpvp | 1000 |
| Cenozoic, Tertiary, Pre-Pliocene, Sierran volcanic rocks | Basalt | Tsvb, Tsv | 2000 |
| Cenozoic, Tertiary, Pre-Pliocene, Sierran volcanic rocks | Andesite | Tsva | |
| Cenozoic, Tertiary, Pre-Pliocene, Sierran volcanic rocks | Pyroclastic rocks | Tsvp | |
| Cenozoic, Tertiary, Pre-Pliocene | Auriferous gravels | Tag | ? |
| Cenozoic, Tertiary, Pre-Pliocene | Gold Run sandstone | Tgs | ? |
| Cenozoic, Tertiary, Pre-Pliocene | Fort Sage sandstone | Tfs | ? |
| Mesozoic, Jurassic to Cretaceous, Basement complex | Granitic rocks | JKgr | ? |

| Physical characteristics | Water-bearing characteristics |
|---|---|
| Qsd: Loose, wind-blown sand. | Highly permeable but located above water table, hence contains little water. |
| Ql: Unconsolidated silt and clay, contains alkali. | Very low permeability and of little importance to ground water. |
| Qb: Unconsolidated sand, silt, and clay. Often contains alkali. | Low permeability. May yield small amounts of water to domestic wells. |
| Qal: Unconsolidated sand, silt, and gravel with lenses of clay. | Moderate permeability. Yields small to moderate quantities of water to wells. |
| Qls: Unconsolidated mixtures of rock, sand, and clay. | Moderate permeability. May yield moderate quantities of water to wells in Hidden Valley. |
| Qf: Unconsolidated gravel, sand, and silt, with some clay lenses. | Moderate to high permeability. Yields large quantities of water to wells. May contain confined water. |
| Qps: Unconsolidated, poorly cemented, bedded gravel, sand, and silt. | Highly permeable. Frequently occurs above water table. Where saturated yields large quantities of water to wells and sumps. |
| Qpl: Poorly consolidated, bedded sand, silt, and clay. | Permeability ranges from low to high. Contains important aquifers in Honey Lake Valley. Often yields large quantities of water to wells. |
| Qpvb: Jointed basalt flows containing zones of scoria. | Moderate to high permeability. May yield large quantities of water to wells. Acts as forebay for ground water recharge. |
| Qpvp: Bedded mudflows and tuffs. | Low permeability, unimportant to ground water. |
| TQvb: Jointed, fractured flows of vesicular basalt with some pyroclastic rocks. | Moderate permeability, may yield moderate amounts of water to wells. May contain confined water. Important as forebay for ground water recharge. |
| TQvp: Pale-colored bedded tuff. | Unimportant to ground water. |
| Tpl: Bedded, consolidated sandstone, tuffaceous siltstone and diatomite. | Generally of low permeability. Locally may yield moderate quantities of water to wells. Contains confined water. |
| Tpvp: Massive, cemented tuff and mudflows. | Essentially impermeable. |
| Tsvb, Tsva, Tsvp, Tsv: Flows of fractured basalt, andesite, and minor amounts of other types of lava. Massive mudflows and tuffs. | Permeability ranges from poor to moderate. Basalt is generally above zone of saturation, is underlain by impermeable rock and is unimportant to ground water. A few areas may contain perched ground water. Andesite and pyroclastic rocks are essentially impermeable. |
| Tag: Semi-consolidated gravel, sand, and clay. | Low to moderate permeability. Yields water to many springs. Not important to ground water in Honey Lake Valley. |
| Tgs: Semi-consolidated, poorly cemented sandstone and shale. | Low permeability. May yield small quantities of ground water to wells. |
| Tfs: Consolidated, cemented sandstone. | Essentially impermeable. |
| JKgr: Massive, poorly jointed diorite. Locally weathered and decomposed. | Impermeable where fresh. Decomposed rock may yield small quantities of water to wells and sumps. |

Figure 3.--Composite stratigraphic section in Willow Creek Valley and Secret Valley (California Dept. Water Resources, 1963, p. 198). For location of area represented by section, see figure 2.

| GEOLOGIC AGE | | | | GEOLOGIC FORMATION | APPROXIMATE THICKNESS IN FEET |
|---|---|---|---|---|---|
| CENOZOIC | QUATERNARY | RECENT | | SAND DUNES | 0-25 |
| | | | | LAKE DEPOSITS | 0-100 |
| | | | | LANDSLIDE | 0-50 |
| | | | | BASIN DEPOSITS | 0-150 |
| | | | | INTERMEDIATE ALLUVIUM | 0-250 |
| | | | | ALLUVIAL FANS | 0-250 |
| | | | | RECENT BASALT | 0-250 |
| | | Pleistocene | Pleistocene Volcanic Rocks | BASALT | 0-100 |
| | | | | PYROCLASTIC ROCKS | 0-250 |
| | | Plio-Pleistocene | Plio-Pleistocene Volcanic Rocks | BASALT | ? |
| | | | | PYROCLASTIC ROCKS | ? |
| | TERTIARY | PLIOCENE | | PLIOCENE LAKE DEPOSITS | 1000 |
| | | | PLIOCENE VOLCANIC ROCKS | ANDESITE | ? |
| | | | | BASALT | ? |
| | | | | PYROCLASTIC ROCKS | ? |
| MESOZOIC | JURASSIC TO CRETACEOUS | | BASEMENT COMPLEX | GRANITIC ROCKS | ? |
| | PRE-CRETACEOUS | | | METAMORPHIC ROCKS | ? |

STRATIGRAPHY


| PHYSICAL CHARACTERISTICS | WATER-BEARING CHARACTERISTICS |
|---|---|
| Qsd: Unconsolidated, thin deposits of wind-blown sand. Found only along shore of Eagle Lake. | High permeability but underlain by impermeable material. Of no importance to ground water. |
| Ql: Unconsolidated silt and clay. | Very low permeability. Of very little importance to ground water. |
| Qls: Unconsolidated sand, clay, and blocks of basalt. | Moderate permeability but of little importance to ground water. |
| Qb: Unconsolidated silt, clay, sand, and organic muck. | Low permeability. Yields small supplies of ground water to stock and domestic wells. |
| Qal: In Secret Valley, unconsolidated sand, silt, and clay; up to 50 feet in thickness. In Willow Creek Valley, unconsolidated sand, silt, and lenses of gravel; up to 250 feet in thickness. | In Secret Valley, of low permeability and yields small amounts of water to wells. In Willow Creek Valley, moderately permeable and yields moderate amounts of water to wells. |
| Qf: In Secret Valley, unconsolidated gravel, fine sand, and clay; up to 50 feet in thickness. In Willow Creek Valley, unconsolidated gravel, sand, and clay; up to 250 feet in thickness. | In Secret Valley, of moderate permeability and yields moderate amounts of water to wells. In Willow Creek Valley, of moderate to high permeability and yields moderate to large amounts of water to wells. |
| Qrvb: Highly fractured basalt containing many zones of scoria. | Highly permeable. Could transmit large quantities of ground water to wells. |
| Qpvb: Fractured flows of basalt containing zones of scoria. | Moderate to high permeability. Could transmit large amounts of ground water to wells. May contain confined water. |
| Qpvp: Semiconsolidated cinders and tuff. Occurs mainly as cinder cones. | Of little importance to ground water. |
| TQvb: Cones and flows of jointed vesicular basalt. | Highly permeable. Acts as recharge area. May provide large amounts of ground water to wells. May contain confined water. |
| TQvp: Pale-colored, bedded tuff. | Unimportant to ground water. |
| Tpl: Beds of consolidated shale, sandstone, diatomite, and lenses of gravel. | Low overall permeability. Yields sufficient water only for domestic and stock purposes. Gravel lenses moderately permeable and could provide moderate quantities of semiconfined ground water. |
| Tpva: Massive flows and plugs of andesite. | Unimportant to ground water. |
| Tpvb: Highly jointed flows, dikes, and necks of basalt. Contains zones of scoria. | Moderate permeability. Could yield moderate amounts of confined ground water to wells. |
| Tpvp: Beds of consolidated tuff. | Unimportant to ground water. |
| JKgr: Hard, nonweathered granitic rocks. Soft, weathered, decomposed granite. | Where nonweathered, rock is essentially impermeable. Some water transmitted along joints. Where decomposed, rock is of low permeability, and capable of transmitting very small amounts of ground water. |
| pKm: Massive, metamorphosed andesite and rhyolite. | Essentially impermeable. |

delicate

FROM CAL. DEPT OF WATER RES. (1963) p19

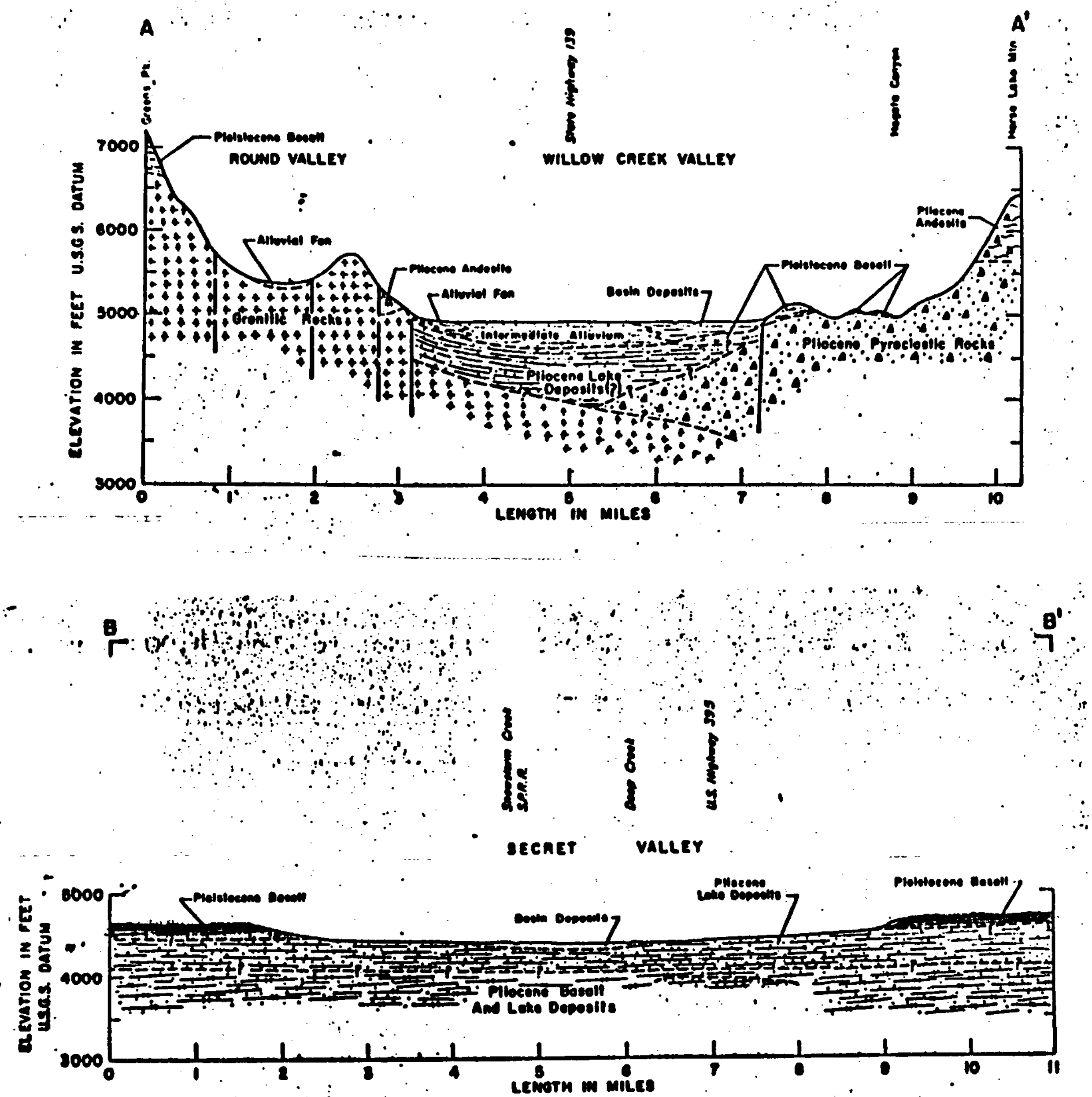
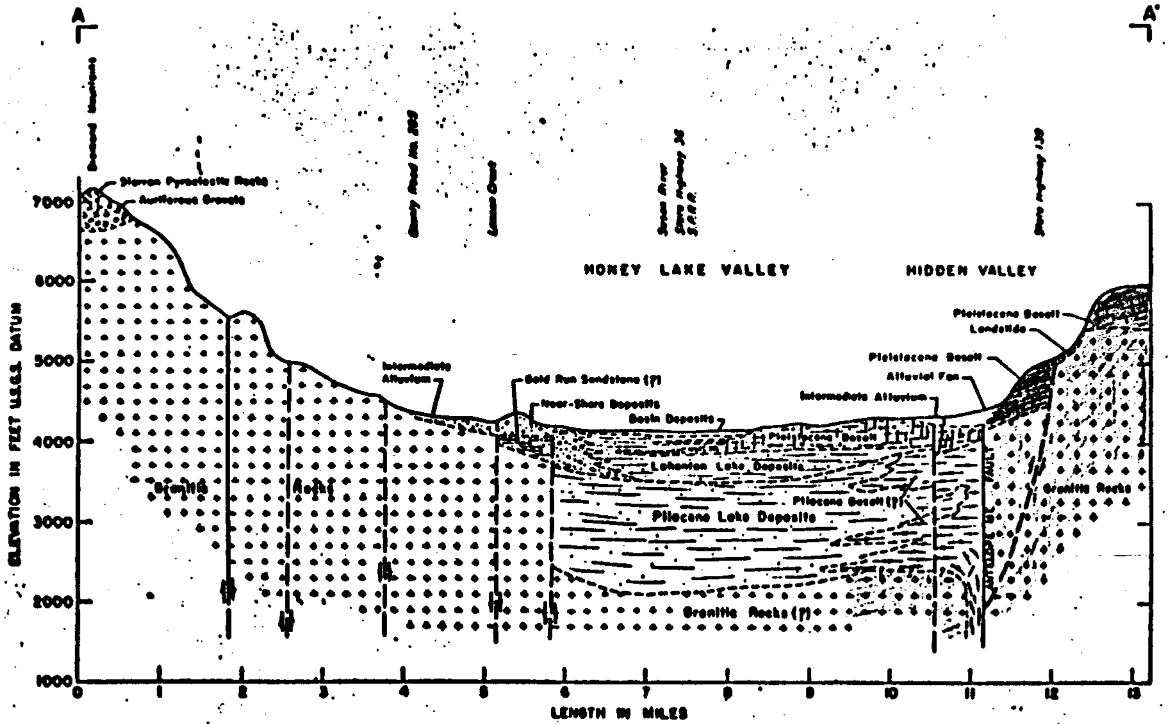



Figure 5.--Generalized geologic sections across Willow Creek Valley and Secret Valley (California Dept. Water Resources, 1963, p. 202). For locations see figure 2



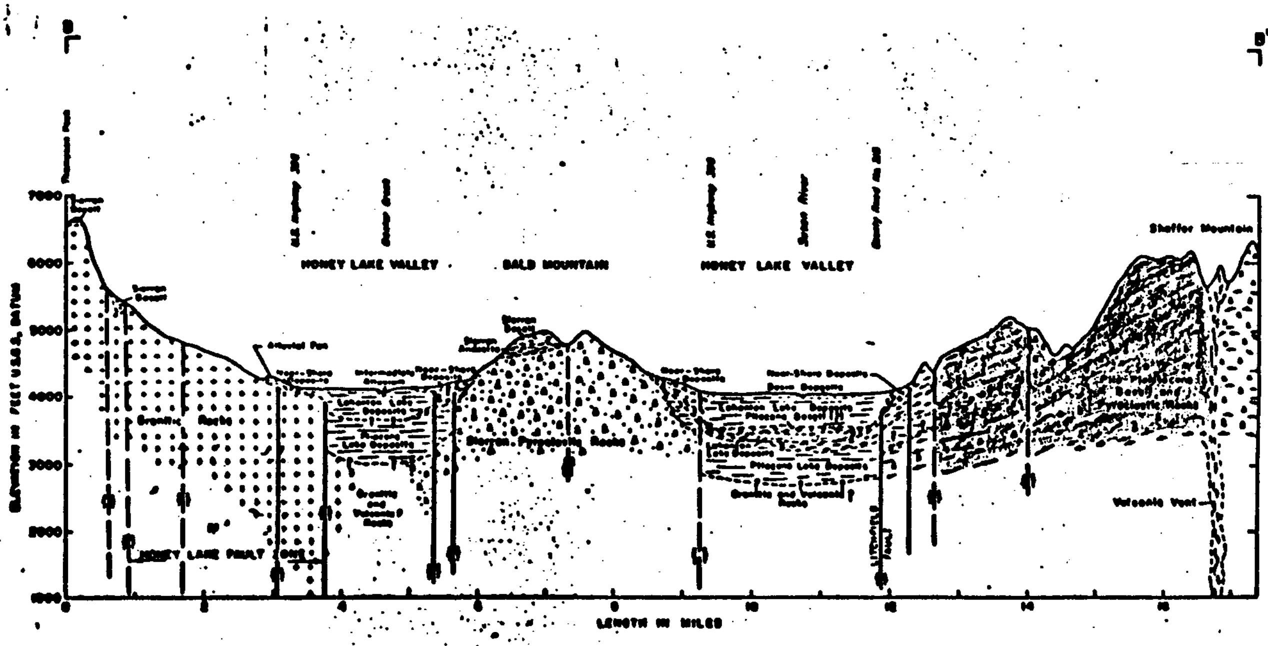




Figure 6.--Generalized geologic sections across Honey Lake Valley (California Dept. Water Resources, 1963, p. 211). For location see figure 2.

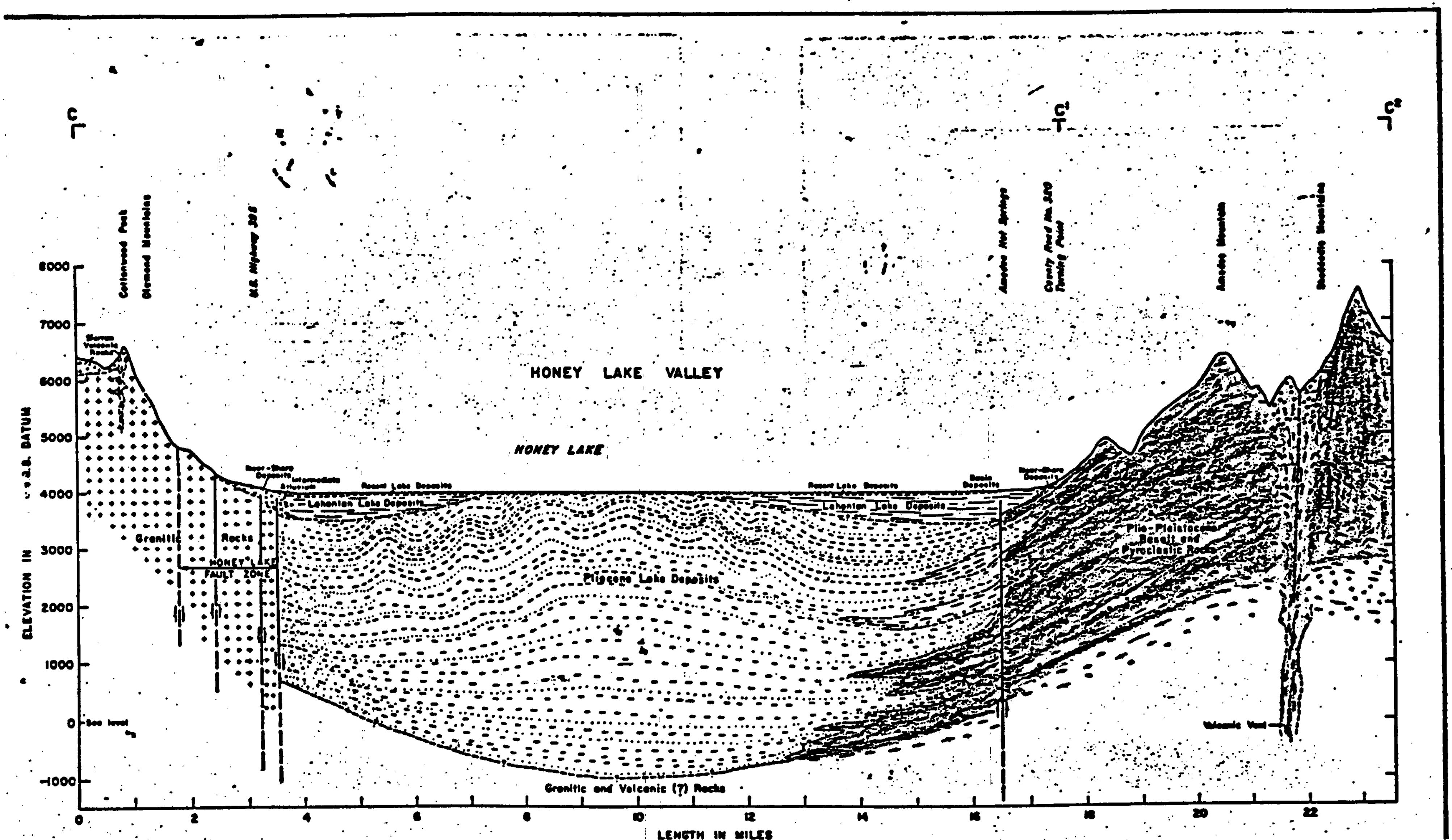
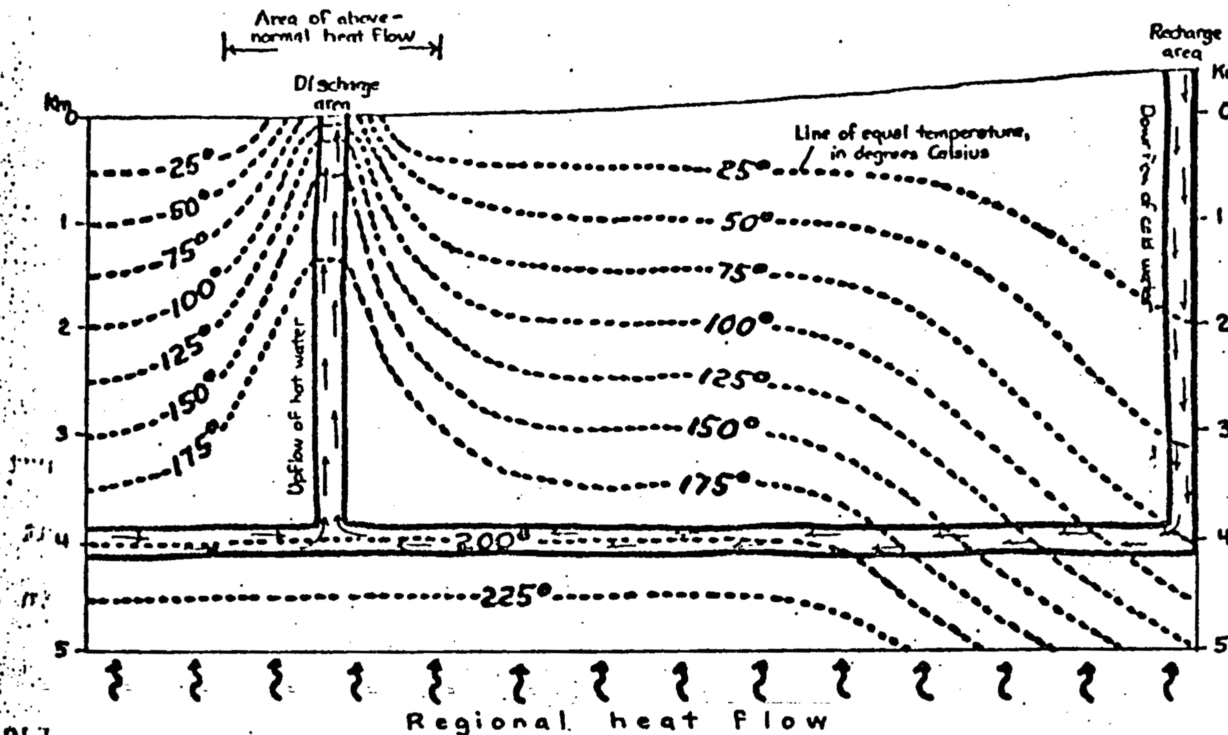



Figure 7.--Generalized geologic section across Honey Lake Valley (California Dept. Water Resources, 1963, p.2-12). For location see figure 2.



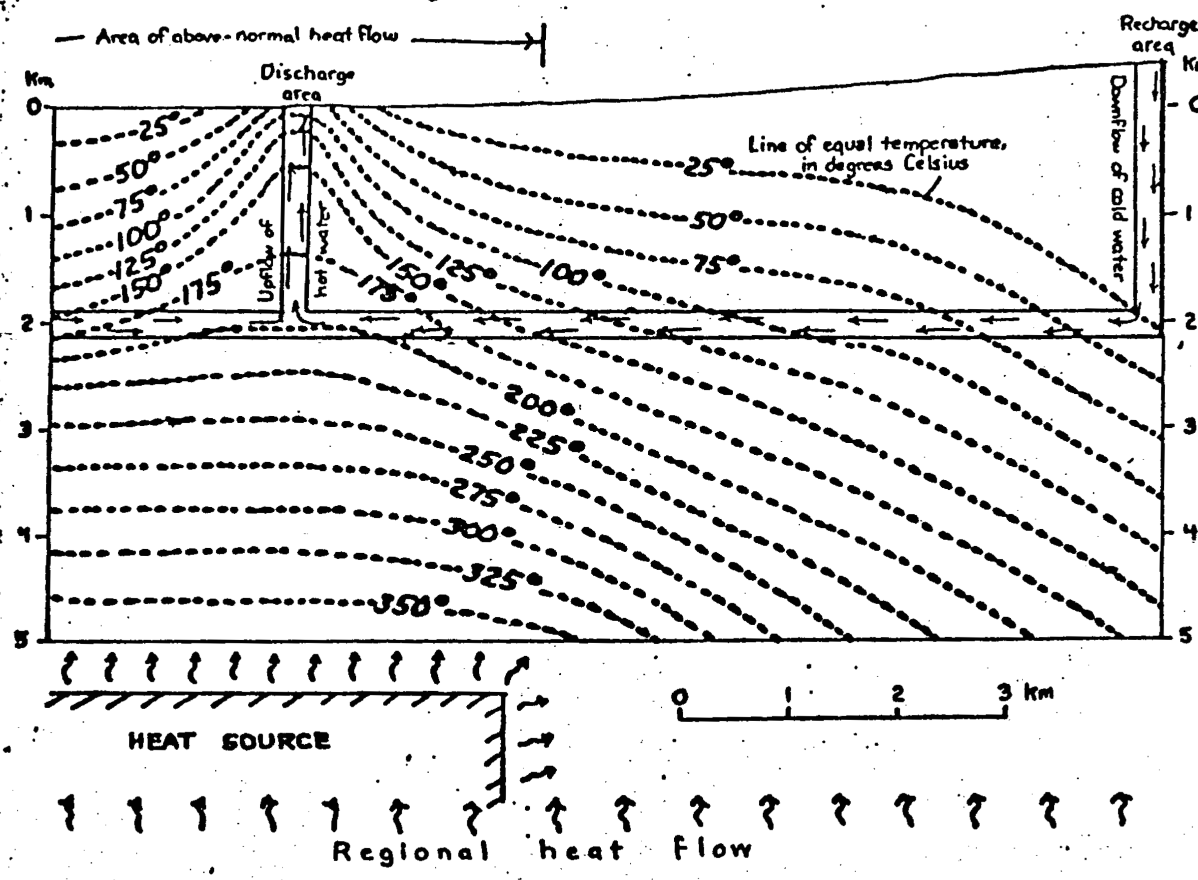
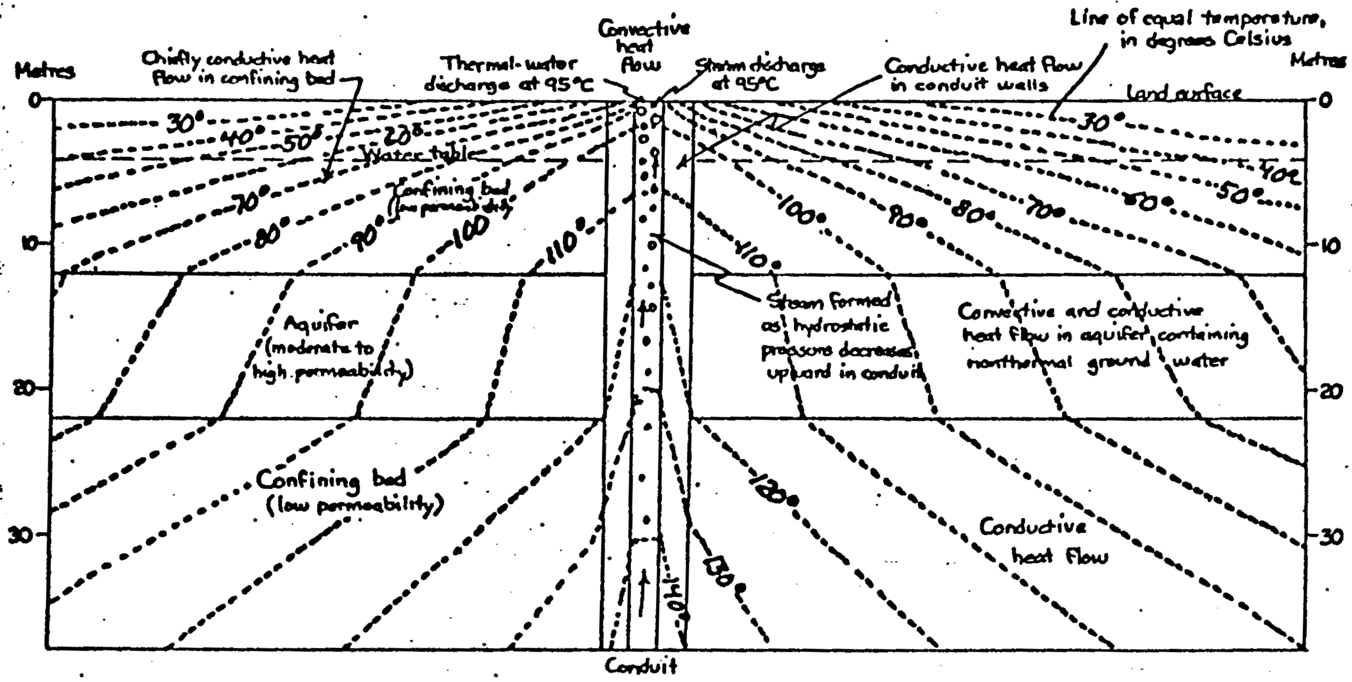




Figure 9.--Conceptual models for the source of heat in hydrothermal systems (Olmsted and others, 1975, p. 50).

A (top), Diagrammatic cross section of hydrothermal system lacking a heat source in the shallow crust.

B (bottom), Diagrammatic cross section of hydrothermal system having a heat source in the shallow crust.



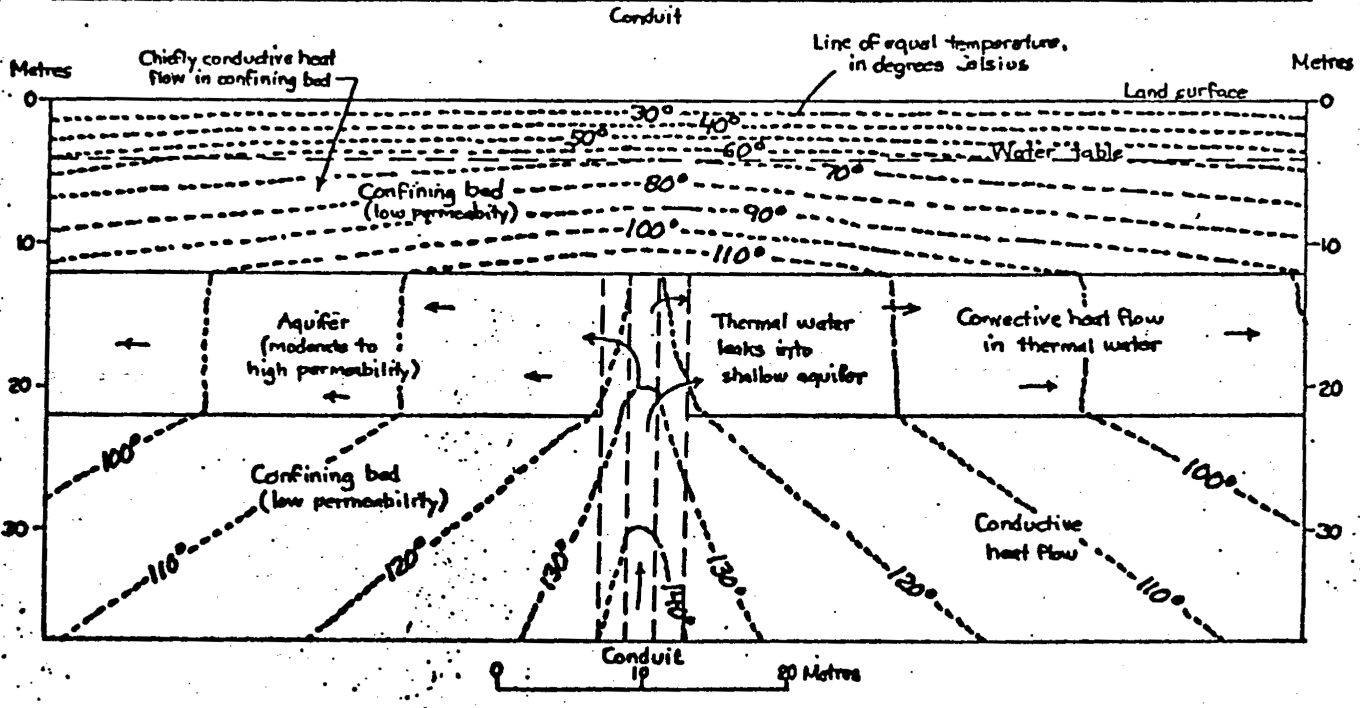




Figure 10.--Conceptual models for discharge of two hydrothermal systems (Olmsted and others, 1975, p. 55).

A (top), Diagrammatic cross section of a hydrothermal discharge system having a nonleaky discharge conduit.

B (bottom), Diagrammatic cross section of a hydrothermal discharge system having a leaky discharge conduit.

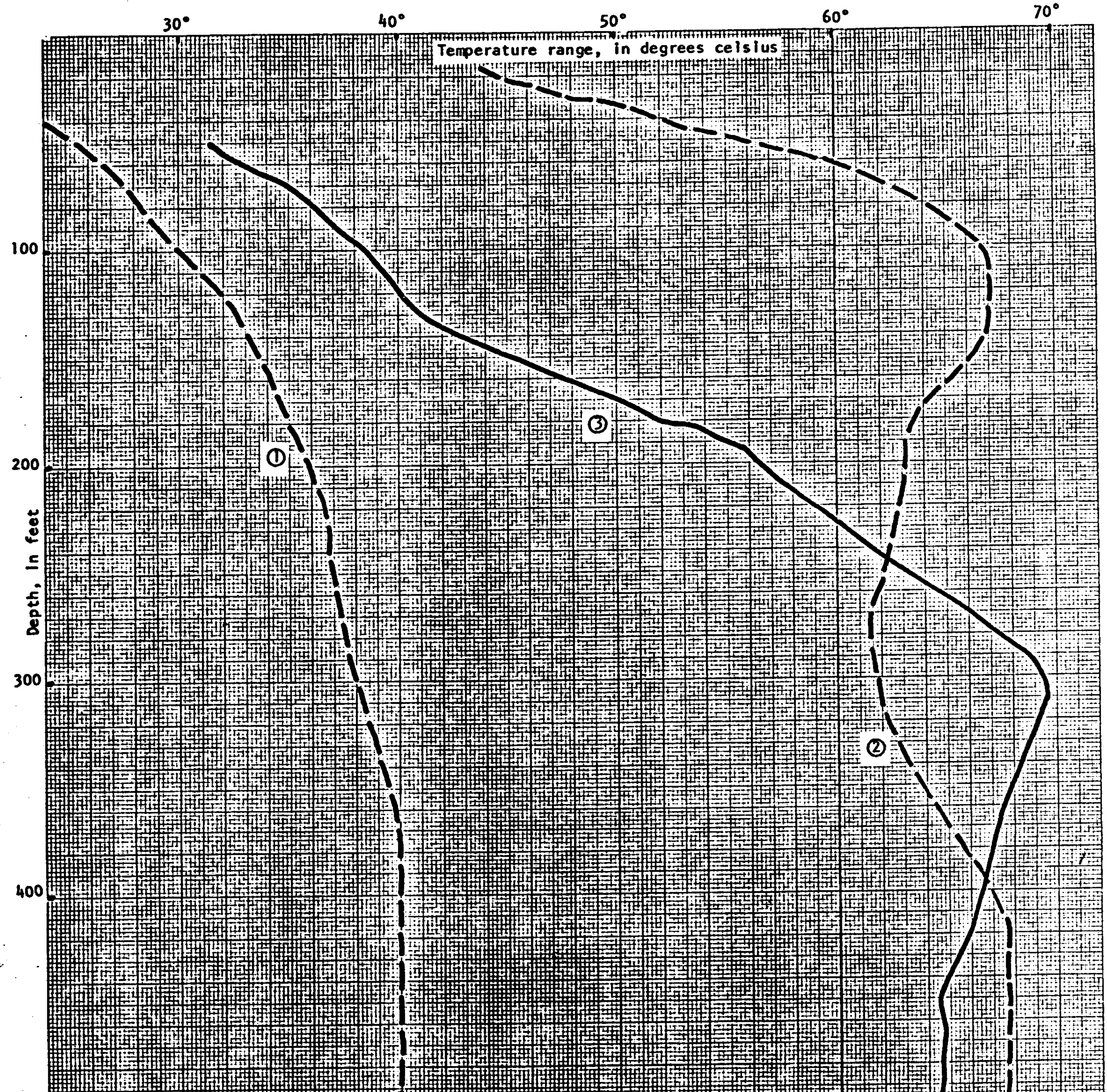



Figure 11.--Temperature profiles in three thermal wells in Susanville (Bureau of Reclamation, written commun., 1975).

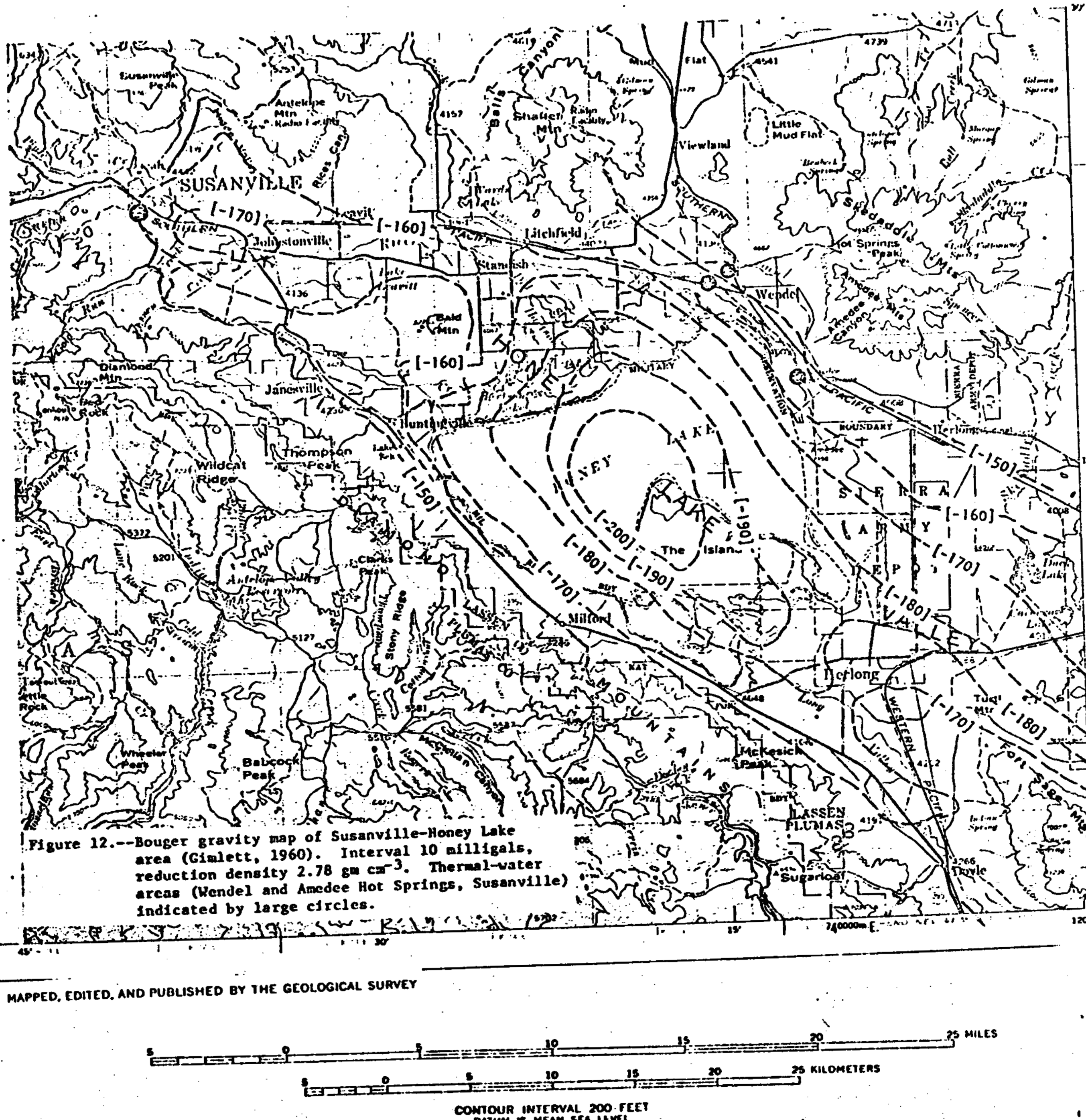



Figure 12.--Bouger gravity map of Susanville-Honey Lake area (Gimlett, 1960). Interval 10 milligals, reduction density 2.78 gm cm$^{-3}$. Thermal-water areas (Wendel and Amedee Hot Springs, Susanville) indicated by large circles.

CONTOUR INTERVAL 200 FEET
DATUM IS MEAN SEA LEVEL

SUSANVILLE, CALIFORNIA
N4000—W12000/60x120
1962


Figure 13.--Resistivity map of the Susanville-Honey Lake area (U.S. Bureau of Reclamation, written commun., 1975). Resistivity in ohm-ft, interval 10 ohm-ft. Thermal-water areas (Wendel and Amedee Hot Springs, Susanville) indicated by large circles.

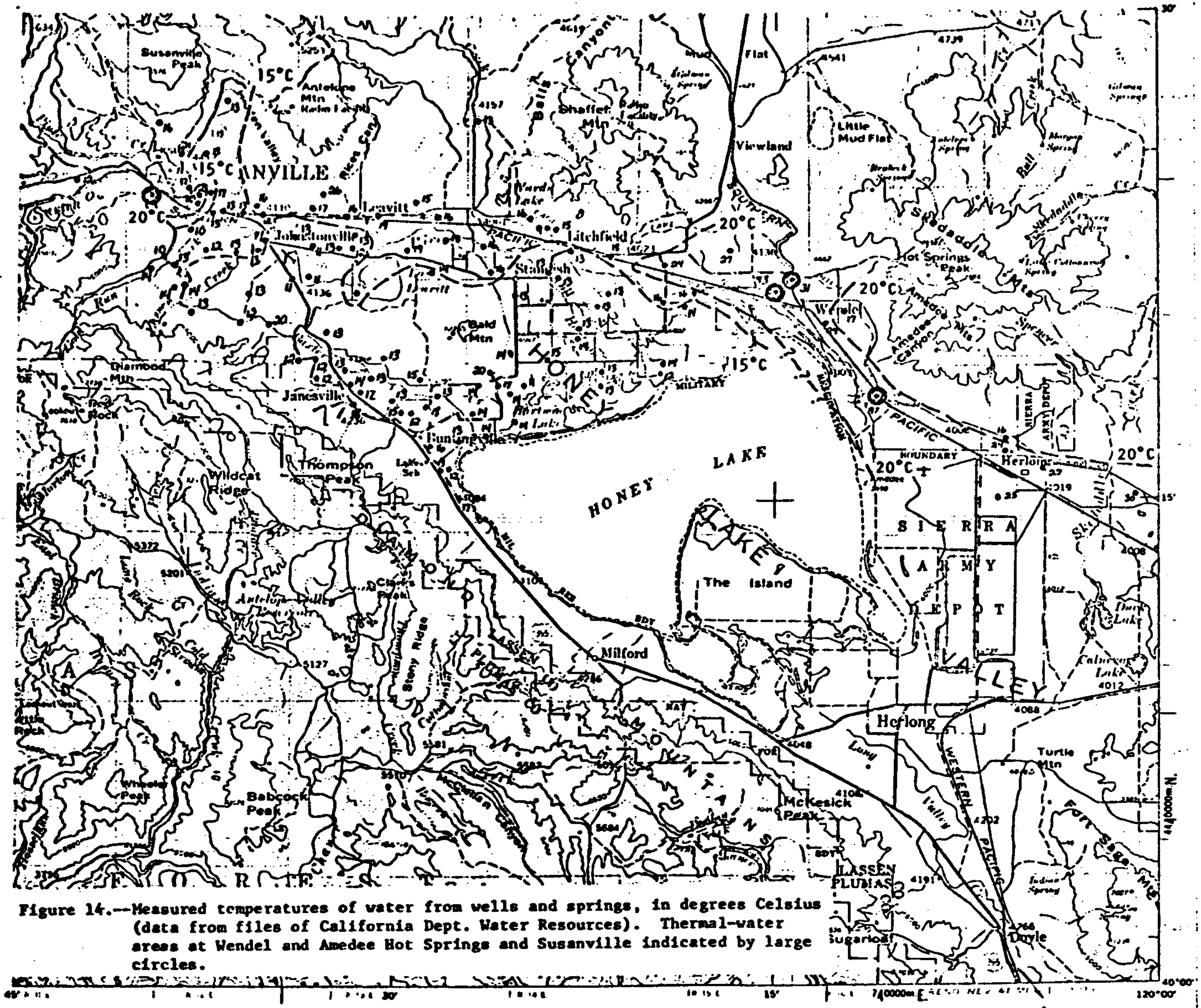



Figure 14.--Measured temperatures of water from wells and springs, in degrees Celsius (data from files of California Dept. Water Resources). Thermal-water areas at Wendel and Amedee Hot Springs and Susanville indicated by large circles.

MAPPED, EDITED, AND PUBLISHED BY THE GEOLOGICAL SURVEY

5 0 5 10 15 20 25 MILES

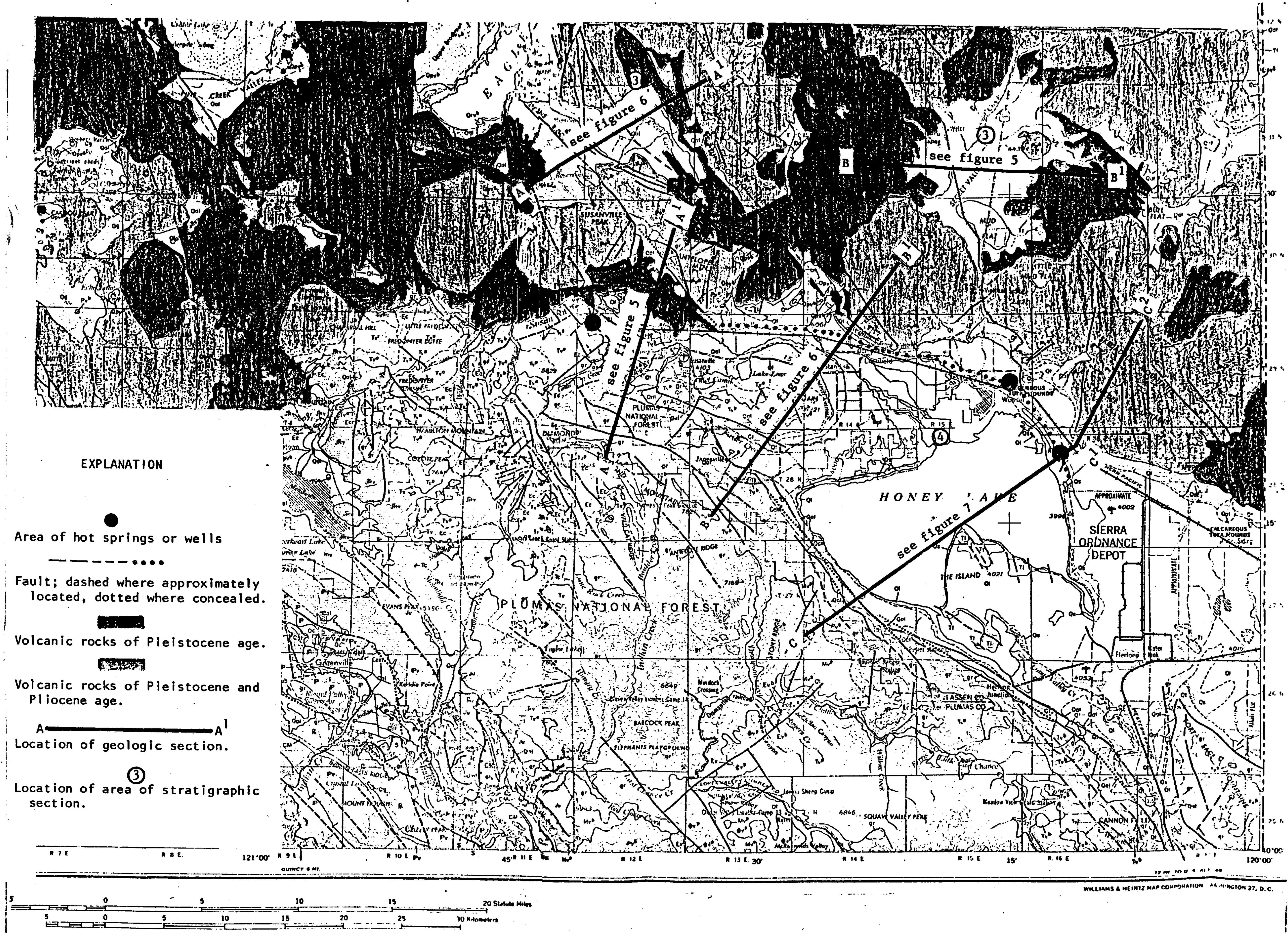
5 0 5 10 15 20 25 KILOMETERS

CONTOUR INTERVAL 200 FEET
DATUM IS MEAN SEA LEVEL

1962 MAGNETIC DECLINATION FOR THIS SHEET VARIES FROM 18°30' EASTERLY FOR THE CENTER OF THE WEST EDGE TO 18°15' EASTERLY FOR THE CENTER OF THE EAST EDGE. MEAN ANNUAL CHANGE IS 0°01' WESTERLY

SUSANVILLE, CALIFORNIA
N4000—W12000/60x120

1962




CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

GEOLOGIC MAP OF CALIFORNIA
OLAF P. JENKINS EDITION
WESTWOOD SHEET
COMPILATION BY P.A. LYDON, T.E. GAY, JR. AND C.W. JENNINGS 1960

Figure 2.--Geologic map of the region north of the Susanville-Honey Lake area, showing locations of geologic and stratigraphic sections (southeastern part of Westwood Sheet (Lydon and others, 1960) of California Division of Mines and Geology, Geologic Map of California). Stratigraphic sections are shown in figures 3 and 4, and geologic sections in figures 5-7.

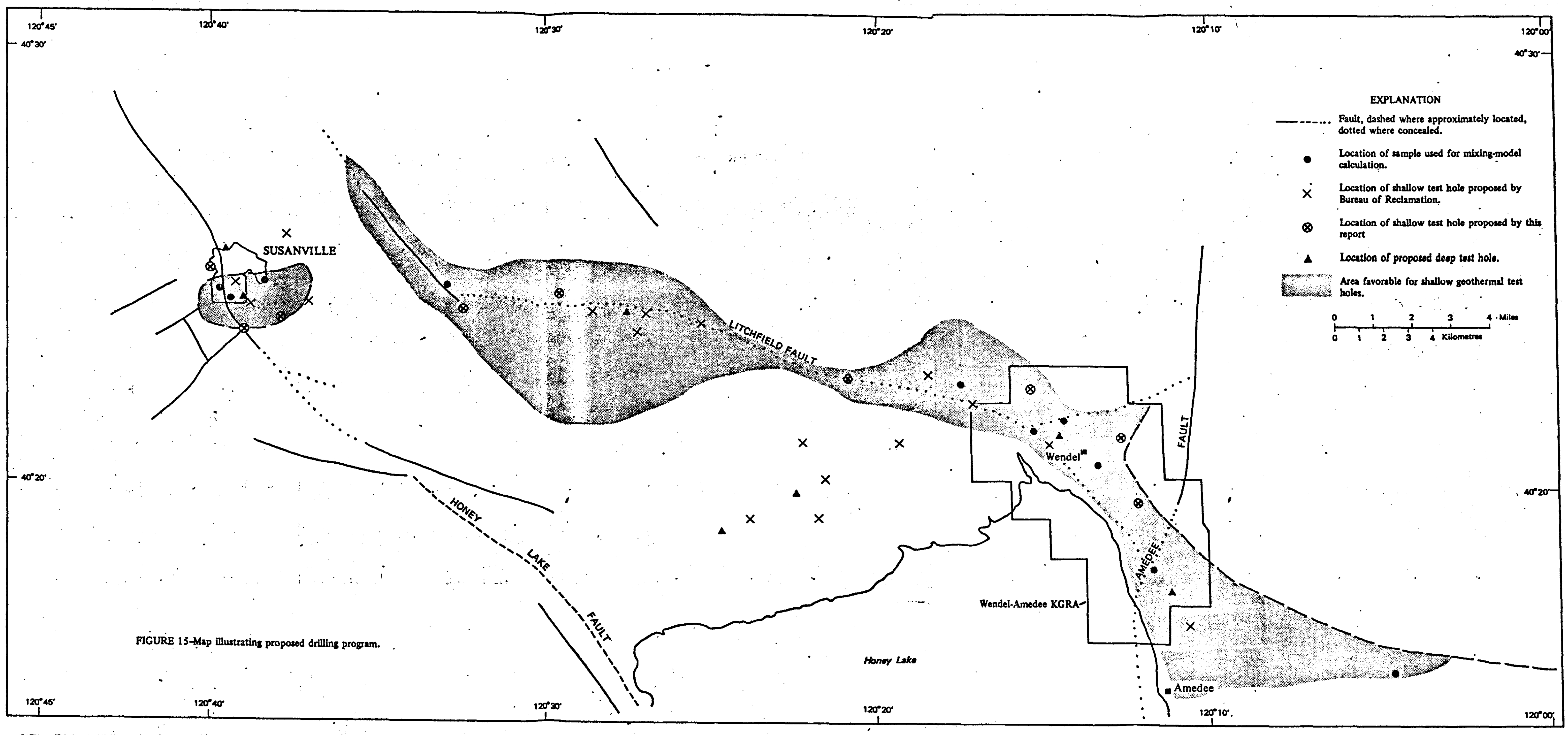



FIGURE 15–Map illustrating proposed drilling program.

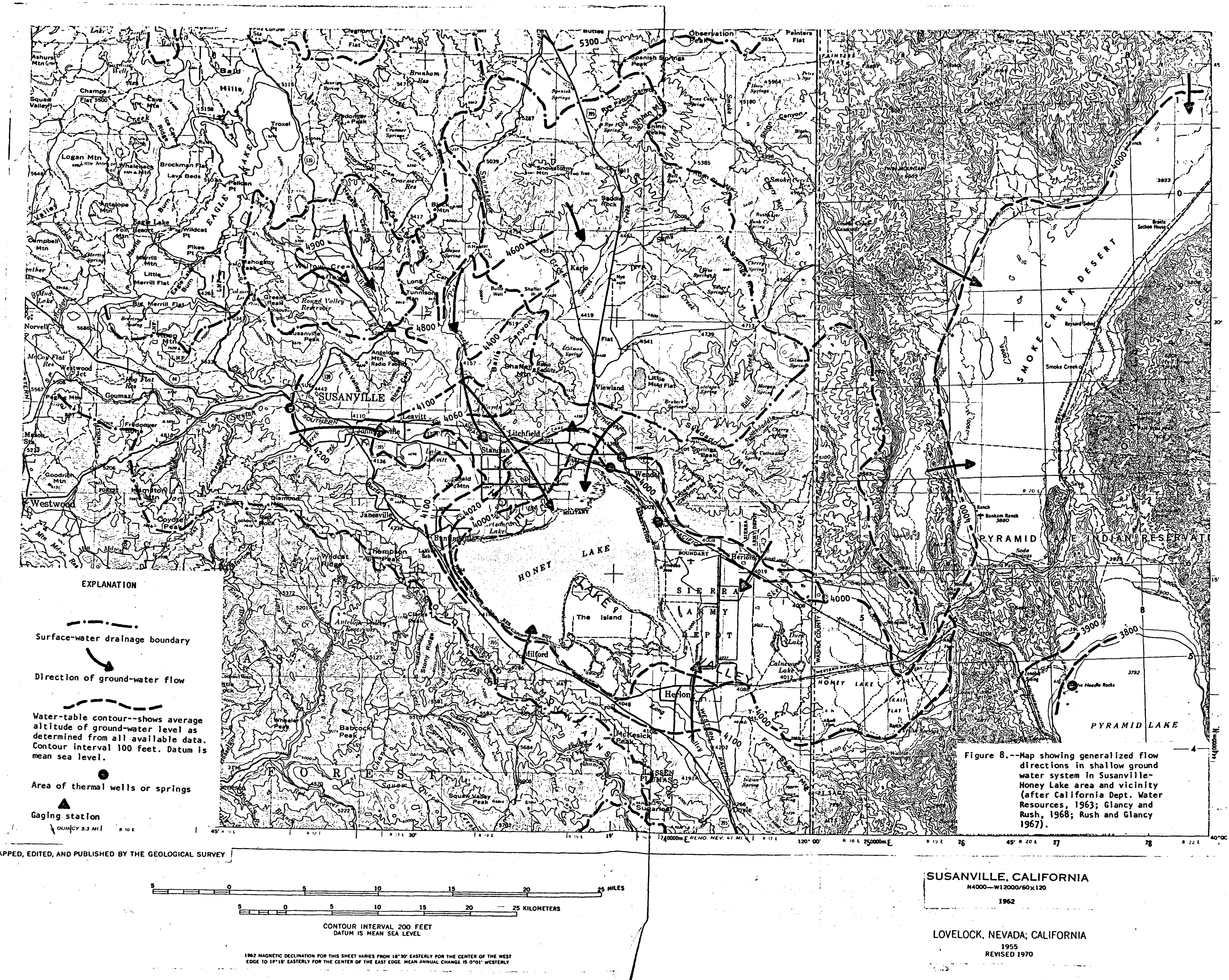



Figure 8.--Map showing generalized flow directions in shallow ground water system in Susanville-Honey Lake area and vicinity (after California Dept. Water Resources, 1963; Glancy and Rush, 1968; Rush and Glancy 1967).