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Geothermal Regimes of the
Clearlake Region, Northern California

Los Alamos
NATIONAL LABORATORY

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ABSTRACT

The first commercial production of power from geothermal energy, at The Geysers steamfield in northern California in June 1960, was a triumph for the geothermal exploration industry. Before and since, there has been a search for further sources of commercial geothermal power in The Geysers–Clear Lake geothermal area surrounding The Geysers. Geothermal corporations have searched for high-temperature resources at depth, especially for extensions and repetitions of the steamfield. Local government jurisdictions, particularly Lake County and the City of Clearlake, mainly with the financial support of the California Energy Commission, have sought commercial low-temperature resources at shallow depth. As a result of the exploration, the contiguous production area at The Geysers was expanded, but in the surrounding area, no important new commercial developments resulted. As with all exploration programs, these were driven by models. The models in this case were of geothermal regimes, that is, the geometric distribution of temperature and permeability at depth, and estimates of the physical conditions in subsurface fluids. The regimes were predicted from scientific information gathered in the disciplines of geology, geophysics, and geochemistry. In general, the studies in geology and potential-field geophysics yielded little information of immediate relevance, but results of electromagnetic surveys were equivocal. Studies in microseismicity and heat flow, however, did yield geophysical information relevent to active geothermal systems. Studies in stable-element geochemistry found hiatuses or "divides" at the Stoney Creek Fault and at the Collayomi Fault. In the region between the two faults, early speculation as to the presence of steamfields was disproved from the geochemical data, and the potential existence of hot-water systems was predicted. Studies in isotope geochemistry found the region was characterized by an isotope mixing trend. The combined geochemical data have negative implications for the existence of extensive hydrothermal systems and imply that fluids of deep origin are confined to small, localized systems adjacent to faults that act as conduits. There are also shallow hot-water aquifers. Outside fault-localized systems and hot-water aquifers, the area is an expanse of impermeable rock. The extraction of energy from the impermeable rock will require the development and application of new methods of reservoir creation and heat extraction such as hot dry rock technology.

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I. INTRODUCTION

A. Terms of Reference

The most productive source of geothermal power in the United States is The Geysers steamfield in northern California. Electric power is produced by traditional "steam-generation" technology, which uses the pressure of the vapor to drive turbines at the surface.

The vapor pressure in the steamfield declines with cumulative production, so without intervention, The Geysers is a failing resource. For many years, condensates from the power plants were reinjected into the reservoir at depth. This reinjection program was recently expanded substantially to include water transported from sewage treatment plants to the east. This measure will prolong the life of the steamfield, and may significantly increase the proportion of heat recovered from the rocks in the steamfield. However, it will require substantial supplies of water and will not recover heat from impermeable rocks outside the reservoir.

There is a region of high geothermal heat flow surrounding the steamfield at The Geysers, which is not commercially productive. Exploration for additional steamfields was unsuccessful. One hot-water spring was unsuccessfully explored for its potential for power generation. Two warm-water aquifers were explored, and one was developed for direct-use applications, but the enthalpy of the fluid was insufficient for commercial electric power generation.

Hot dry rock (HDR) technology was developed by Los Alamos National Laboratory at the Fenton Hill site, in the Jemez Mountains of northern New Mexico. It produced power at a rate of about 4 MWt (megawatts thermal) from an artificial reservoir in Precambrian granite gneiss. The depth range was 3.35 to 3.66 km (10,900 to 12,000 ft), and the corresponding temperature range was 231°C to 243°C (445°F to 469°F).

HDR technology was a significant enhancement of geothermal technology. It demonstrated that lack of natural permeability in the rock at depth was not a total block to geothermal power development. A reservoir could be created by hydraulic stimulation in the hardest rock. The lack of natural fluids in the rock was not a bar to development. The fluid losses at Fenton Hill were low enough that the HDR plant did not require copious supplies of water.

The possibility arose that HDR technology might produce power where other methods had failed, in the impermeable hot rocks surrounding The Geysers steamfield. This report is one of a series that examines the possibility.

Since this project began, new concepts have emerged in engineered geothermal systems, particularly the hot wet rock concept of Abe and Hayashi (1992), which was introduced to deal with problems of leaky reservoirs. The SE Geysers effluent pipeline has come to fruition (Dellinger, 1993), to deal with problems of water depletion at The Geysers steamfield. Other advanced geothermal engineering systems are in various stages of development from the concept stage to field tests. In finalizing this report, we have taken into account some of these new developments.

Previous reports in this project include Brown and Burns (1994), Burns (1991, 1992), Burns and Potter (1990, 1993), Burns, Potter, and Peake (1995), and Burns, Potter, and Zyvoloski (1992). Previous reports in this present series include Goff, Adams, Trujillo, Counce, and Mansfield (1993), Jager (1996), and Burns (1996, April and August).

This work was conducted for the City of Clearlake with funds provided by the California Energy Commission, Geothermal Grants and Loan Program. This report is the final report for Phase 2, Task E, Geothermal Regimes.

B. Scope of This Report

A geothermal regime is a fluid circulation system, involving inflows and outflows of fluid, residence time in underground reservoirs, and circulation within reservoirs driven by metamorphic stress, magmatic gas pressure, or thermal bouyancy. This report reviews previous work in geology, geophysics, and geochemistry regarding geothermal regimes in The Geysers–Clear Lake region. It does not address engineering work relating to the mechanical and hydraulic properties of rocks during exploration drilling.

This report does not gather any new data or make any new compilations. The purpose is to discover what work has been done and what conclusions were reached by the different investigators. One question is whether previous work truly established the need for advanced geothermal production techniques, such as HDR. Another question is whether it revealed any characteristics of the rocks that would disqualify HDR as a technology of choice for advanced geothermal development.

There was intensive geothermal exploration in The Geysers–Clear Lake area in the period from about 1973 to 1985. In that time, about 17 deep wells were drilled, some to depths exceeding 10,000 ft, and over 700 geothermal gradient wells, for a total cost said to have exceeded $60 million. Part of that information is publicly available in statutory archives and in city and county records. However, much of it is unpublished, is sometimes fragmentary, and is scattered through numerous informal private archives. In our quest to understand what transpired in the various exploration programs, we have been very generously provided with information from numerous sources. This report is well short of a complete coverage; however, we hope it is a useful representative sample.

C. Geographic Nomenclature

John C. Fremont's expedition of 1847 discovered geothermal manifestations in northern California and named the locality "The Geysers." This form, with the capitalized definite article, has become traditional and is widely used in the geothermal literature. In 1957, drilling discovered a steamfield at depth known as "The Geysers steamfield." The area of high heat flow, which includes The Geysers steamfield and extends in the northeast direction beyond Clear Lake, is known as "The Geysers–Clear Lake geothermal field." The administrative district that includes and surrounds The Geysers–Clear Lake geothermal field is named "The Geysers–Clear Lake Known Geothermal Resource Area," or "The Geysers–Clear Lake KGRA" (Koenig, 1992, Fig. 1, p. 8).

Clear Lake has a large circular basin at the northern end and two arms. The eastern extension is Oaks Arm, and on the northern shore is the town of Clearlake Oaks. The southeastern area is Highlands Arm, and on the northeastern shore was the township of Clearlake Highlands, which became incorporated as the City of Clearlake. The name "Clear Lake" applies to the lake and to the volcanic field on its western side. The name "Clearlake" is used for the city and its surrounding region.

One of the Coast Ranges, the Mayacmas Mountains, trends northwest-southeast across the southwest part of the region of interest in northern California. One of the creeks draining the southwestern slope of the Mayacmas Mountains, near Jimtown, is named Maacama Creek. A major fault of the San Andreas system, the Maacama Fault Zone, bounds the

Mayacmas Mountains on the west. The name "Maacama Antiform" has been applied to a geological structure running through The Geysers steamfield.

On the northeastern side of the Mayacmas Mountains, near Middletown, is Collayomi Valley. The name "Collayomi Fault" has been applied to a geological structure running through the valley and up Putah Creek. Collayomi is also the name of a land parcel occupying the valley. Caslamayomi is another land parcel inside the Mayacmas Mountains.

Two Sulphur Banks are described in this report. One is the Sulphur Bank area of The Geysers, situated in the western Mayacmas Mountains. The other is the Sulphur Bank sulphur and mercury mine and hot spring, situated on the south side of Oaks Arm of Clear Lake. The term "sulphur bank" is also used colloquially to describe any area of hydrothermal leaching and alteration near hot springs.

The bedrock geology throughout most of the Coast Ranges is composed of Franciscan rocks of Jurassic-Cretaceous age. These are divided into three provinces. The "Coastal province" extends from the Pacific coastline inland, as far as about Healdsburg. The "Central province" extends from there east to about Highlands Arm of Clear Lake. The "Eastern province" extends east from Clear Lake to the boundary of the Central Valley near Wilbur Springs. The principal change from west to east is an increasing degree of metamorphism, induration, and fabric intensity, which decreases abruptly again on entering the Great Valley sequence rocks of the Central Valley and in inliers of Great Valley rocks within the Coast Ranges.

D. Geothermal Waters

Thermal waters are natural waters at temperatures greater than the ambient air temperature. The average annual temperature is 13°C at Upper Lake (Brice, 1953), so thermal waters in this district are those with temperatures greater than 13°C.

Thermal waters near Clearlake were defined as low, intermediate, or high chloride. Low-chloride waters had Cl<1,200 mg/L; intermediate waters had Cl content between 1,990 and 4,000 mg/L; and high-chloride waters had Cl>8,000 mg/L (Beall, 1985).

The terms "magmatic," "connate," and "metamorphic" were developed by White (1957a,b) to describe geothermal waters from different sources. Magmatic waters, high in sodium chloride, originated from gases driven at high temperature and pressure from magma. Connate waters, or high-chloride "fossil seawater," dominated by sodium and calcium chloride, were trapped in sediments during deposition and driven out by compaction. Metamorphic waters were due to dehydration of hydrous minerals during metamorphism after interstitial connate water had been driven out (White and Roberson, 1962). Chemical and isotope signatures of the various sources in The Geysers–Clear Lake area were described by White, Barnes, and O'Neil (1973) and were reviewed for this project by Goff, Adams, Trujillo, Counce, and Mansfield (1993).

Geothermometers: The Na-K-Ca temperature of Fournier and Truesdell (1973, Fig. 6, p. 1266) is included in the tables of this report. The basic assumptions of the method were described by Fournier, White, and Truesdell (1974). The tables in this report were calculated using the formula and algorithm to select the parameter β of Fournier (1977, Eq. 1, p. 45). Goff, Donnelly, Thompson, and Hearn (1977) explained the algorithm as follows: first, use $\beta = 4/3$, to establish whether the chemical components in the waters are in equilibrium at the measured temperature. If not, then calculate temperature using $\beta = 1/3$ to predict deep reservoir temperature.

The quartz geothermometers of Fournier and Rowe (1966) were calculated using the formulae of Fournier (1977, equations p. 44). The adiabatic quartz-steam model (Qst) was selected for its relevance to high-temperature waters, following Goff, Donnelly, Thompson, and Hearn (1977), and the chalcedony model (Qch) was indicated by a study of quartz solubility in low-temperature waters near the City of Clearlake (Stone, 1987).

Isotope abundances are stated as proportional differences (δ) in per mill notation (‰), which means parts per thousand. The enrichment or depletion of an isotope in a sample, G, relative to a standard, S, is expressed as δG (‰) $= 1{,}000 \ [(R_g - R_s)/R_s]$. For oxygen, the sample ratio is $R_g = {}^{18}O/{}^{16}O$, which is the ratio of weight of oxygen-18 to that of oxygen-16 (Garlick, 1972). For hydrogen, $R_g = D/H$, which is the ratio of weight of deuterium to that of hydrogen (Thatcher, 1972). For both oxygen and hydrogen, the standard ratio R_s is usually the isotope ratio in standard mean ocean water, or SMOW (Craig, 1961), so that δ(SMOW) = 0 per mill.

Heavy isotopes precipitate first from oceanic water vapor, and the vapor that moves inland is depleted in deuterium and oxygen-18. The worldwide correlation between the two isotopes is given by $\delta D = 10 + 8 \times \delta^{18}O$ per mill (Craig, 1961). This trend also applies in the Coast Ranges of northern California (White, Barnes, and O'Neil, 1973; Goff, Adams, Trujillo, Counce, and Mansfield, 1993).

E. Units of Measurement

With the exception of section VIII.B, this report uses SI metric (International System of Units), based upon the report (SPE Metrication Subcommittee, 1977) of the Metrication Subcommittee of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.

(SPE of AIME). Some conversion factors were obtained from Anderson and Lund (1979).

Some data used in this report were converted from original sources to SI using conversion factors as follows: 1 ft (U.S. survey foot) = 0.304 800 6 m, 1 hfu (heat-flow unit, ucal/ s·cm^2) = 41.84 mW/m^2. The thermal conductivity (L) of the bulk rock *in situ* is taken to be 2.97 W/m·K (Walters and Coombs, 1989, Tab. 2, p. 495; 1992 Tab. 2, p. 47).

The most efficient use of the heat energy of geothermal fluid is directly as heat. However, electricity has the attraction of versatility and convenience, so in an advanced industrial society, energy has the greatest value after conversion to electricity despite the losses inherent to the conversion process. Efficiencies of conversion are generally in the range 30% to 60%, with The Geysers' fluids at about 56% (Armstead and Tester, 1987, Fig. 14.3, p. 404). We use the term MWt (megawatts thermal) for the energy content of a fluid before conversion, and MWe (megawatts electric) for the electric power recovered from the fluid. MWhe is megawatt-hours electric. The units may also be written MW(t), MW(e), and MWh(e).

Conversion from English measure to metric is not exact. For example, drillers' logs give depth in drill holes rounded to the nearest foot. A depth, such as 10,042 ft, is strictly a range, from 10,041.5 to 10,042.5 ft. In conversion to meters, 10,042 ft then means the range 3,060.6 to 3,061.0 m. The metric form loses equivalence if rounded, so the metric form needs to be precise to 0.1 m. In the text, we occasionally add the equivalent English measure in parentheses, such as "3,060.8 m (10,042 ft)." This means that the field measurement was rounded English measure. The metric equivalent is the range 0.5 ft to each side of the central value of 3,060.8 m, not the range 0.05 m as might otherwise be expected.

However, we have generally not converted tables of source data. In Tables 5 and 6 in the text of section VIII, some of the measures remain in English form. This is partly in the interest of rounding accuracy and data compression and partly so the information can be more readily identified in the source document.

F. Terminology

Citation designators written in full refer internally to this report, thus "Figure," "Table," "Plate," and "page." Abbreviations, such as "Fig.," "Tab.," "Pl.," and "p." refer to external documents.

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

640-acre sections in a township

We use the nautical cardinal points, quarter and eight points to specify direction; thus, the points in the first quadrant are N, NNE, NE, ENE, and E. Where this is insufficiently precise, we use aeronautical azimuth, expressed in the form N030E, meaning 30° east of north.

Locations are sometimes expressed in areal coordinates on the U.S. land net, such as R7W T13N Sec. 5 MD B&M, meaning Range 7 west, Township 13N, Section 5, Mount Diablo Baseline and Meridian. Townships are subdivided into sections numbered according to the scheme below at left (Badgley, 1959, p. 92); and sections are subdivided into 40-acre blocks numbered A to R as shown below at right (Berkstresser, 1968, Tab. A and Tab. B).

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

40-acre blocks in a section

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II. THE GEYSERS–CLEAR LAKE GEOTHERMAL AREA

A. Introduction

A general locality map of northern California is shown in Figure 1. Geothermal anomalies occur throughout the map, with the largest contiguous anomaly being "The Geysers–Clear Lake Geothermal Area" of McLaughlin and Donnelly-Nolan (1981) or "The Geysers Megadistrict" of Wright (1991). The Geysers–Clear Lake geothermal area extends from the Mayacmas Mountains northeast for 35 km, across Clear Lake into Colusa County.

Several different methods have been used to define the extent of the resource: exploration and production activity, hot springs, and heat flow.

B. Administrative Boundaries

The boundaries of The Geysers steamfield and the surrounding Geysers–Clear Lake geothermal area have been delineated for administrative purposes. The basis for delineation includes leasing, drilling, and production activities as significant factors. Figure 2 shows the boundaries as determined by the California Division of Oil and Gas. Figure 3 shows boundaries of The Geysers–Calistoga, Knoxville, and Witter Springs known geothermal resource areas (KGRAs) as designated by the U.S. Department of the Interior.

Figure 1: Locality map for The Geysers–Clear Lake region of Northern California. Filled triangles are notable peaks; lightly shaded areas are inland lakes. Double lines are major highways; single lines are county boundaries. Heavily shaded areas are extensive urban areas; filled circles are small towns. Some notable springs are SKS = Skaggs Springs, SES = Seigler Hot Springs, GS = Grizzly Springs, and WS = Wilbur Hot Springs. Some notable mercury mines are SBM = Sulphur Bank Mine, AM = Abbott Mine, and EM = Elkin Mine. WT is the site of the Wilbur oil test. Based upon U.S. Geological Survey (1970, 1971).

Figure 2: Geothermal resource area (GRA) of The Geysers area, and administrative boundary of The Geysers geothermal producing field, as determined by the California Division of Oil and Gas, 1981. Based on Stockton, Thomas, Chapman, and Dykstra (1981, Pl. IX).
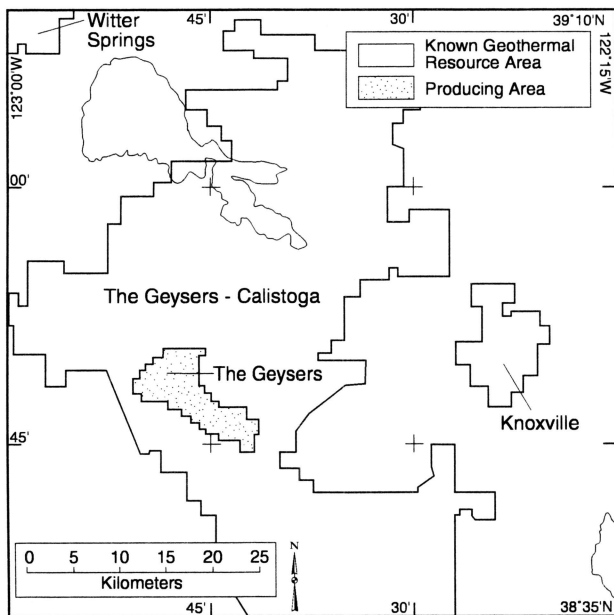
Figure 3: KGRAs of The Geysers–Calistoga, Knoxville, and Witter Springs, as designated by the U.S. Department of the Interior, 1984. Based on Higgins and Martin (1980), Majmundar (1984), and Koenig (1992, Fig. 1, p. 8). Boundary of The Geysers Geothermal (producing) Field based on Hannah (1975, Pl. XI, pp. 38–39).
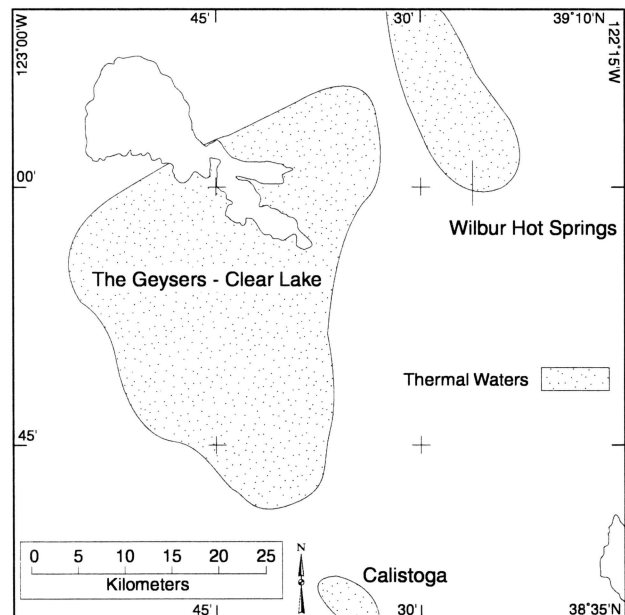
Figure 4: Areas of thermal waters at The Geysers–Clear Lake, Wilbur Hot Springs, and Calistoga, as determined by the California Division of Mines and Geology, 1980. Based on Higgins and Martin (1980) and Majmundar (1984).

C. Hot Spring Boundaries

The simplest geological definition of the resource is to delineate the area containing the most obvious manifestations, which are surface hot springs and fumeroles at the surface, and subsurface hot water found in irrigation and domestic wells. Figure 4 shows the boundaries of The Geysers–Clear Lake, Wilbur Hot Springs, and Calistoga areas of thermal waters as determined by the California Division of Mines and Geology. Thermal waters of sufficient temperature for direct heat applications are known or inferred to underlie these areas.

Figure 5 is a zoning map developed by Lake County for planning purposes, based upon hot spring and drilling information.
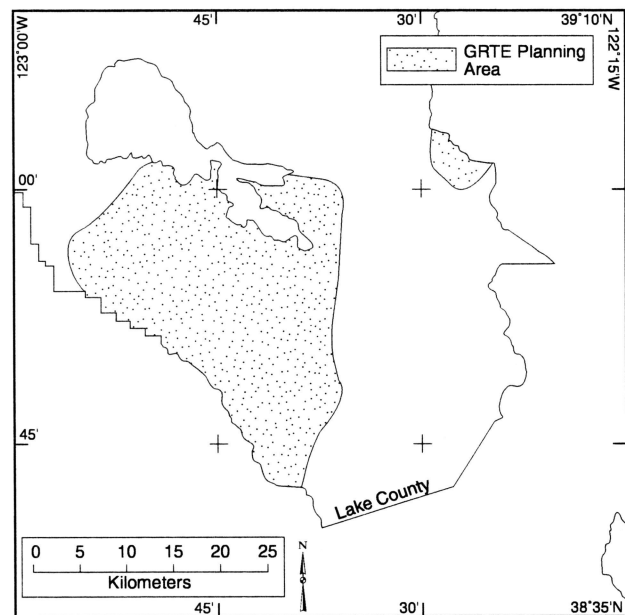
Figure 5: Geothermal Resource Planning Areas of Lake County, 1989. Based on Hinds, Dellinger, Graham, and Seidler (1989, Fig. 1.1-2, pp. 1–4).

D. Heat-Flow Boundaries

The primary geophysical method of delineating the resource is by mapping the heat flow at the surface of the Earth. Figure 6 shows the boundary determined by heat flow of The Geysers–Clear Lake geothermal area as determined by a heat-flow isoline of 167 mW/m² (4 hfu). Wright (1991) termed this area "The Geysers Megadistrict."

Studies of the regional heat flow were reviewed by Burns (August 1996). The heat-flow contour at 167 mW/m² (4 hfu), delineates a zone of melting in the upper mantle. The heat flow inside that contour is sufficient to cause anatexis, or crustal melting, in the overlying rocks, which in turn gives rise to surface volcanism, in the form of the Clear Lake volcanic field, which occupies much of the area between Cobb Mountain and Highland Arm and extends beyond Clear Lake to Round Mountain and Chalk Mountain.

Thomas (1986, Fig. 5, p. 9) found that The Geysers steamfield is delineated by the heat-flow contour at approximately 335 mW/m² (8 hfu). The region outside that, from 335 down to 167 mW/m² (8 down to 4 hfu), is one of conductive heat flow at the surface of the Earth and to a depth of 3 km or more.
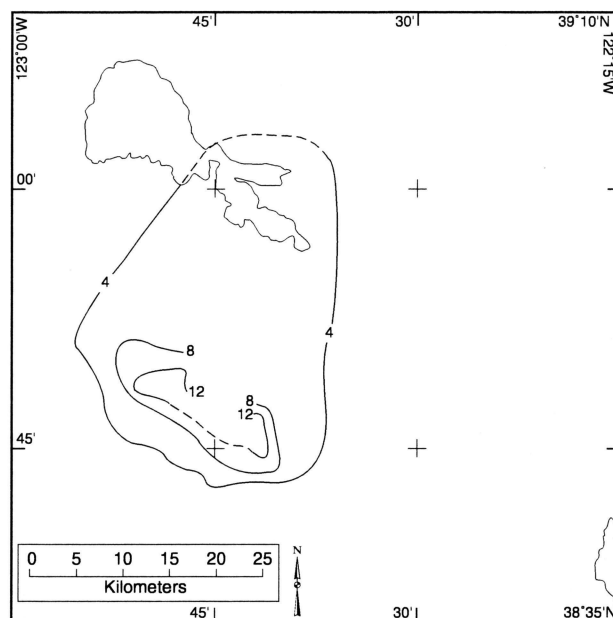
Figure 6: Heat flow in The Geysers–Clear Lake geothermal anomaly, 1989. Contours 4, 8, and 12 hfu (167, 335, and 502 mW/m²). Other anomalous regions near Asti and Wilbur Hot Springs not contoured. Based on Walters and Coombs (1989, Fig. 3, p. 497; 1992, Fig. 3, p. 49). Contours at 8 and 12 hfu derived from Thomas (1986, Fig. 5, p. 9).

R. M. Potter showed also that the resource could be broadly delineated by means of reservoir temperatures inferred from the geochemistry of the thermal waters (Burns and Potter, 1990, Fig. 2, p. 114).

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III. THE STEAMFIELD AT THE GEYSERS AND MT. COBB

A. Introduction

There are two basic types of geothermal reservoirs being used commercially worldwide to produce electric power. One type ("hot-water system") produces hot water from the reservoir. This water is partially flashed at the surface, producing steam to drive the turbogenerators. The two largest installations of this type are Wairekei in New Zealand and Cerro Prieto in Mexico. The second type of reservoir is vapor dominated. The fluid is slightly superheated steam at reservoir ("steamfield") conditions and nearly all the produced fluid is steam, with small amounts of inert gases. The two major installations of this type are at Lardarello in Tuscany and The Geysers in northern California (Brigham and Morrow, 1977).

The Geysers steamfield is the most important geothermal feature in northern California. In 1993, it produced 1,193 MWe from steam (DiPippo, 1995) within the region shown by the dotted boundary in Figure 7. The producing area is elongated, trending about N305E.

B. Geological Characteristics

Geological setting: The Geysers steamfield lies between the Maacama and Collayomi Fault Zones, occupying the northeast limb of a regional Maacama Antiform.

The host rocks are a Franciscan assemblage of Jurassic-Cretaceous age. The assemblage is composed of lithologies that were originally ocean floor sediments (such as graywacke, argillite, and chert) and oceanic crust (such as

greenstone and serpentinite). The lithological bodies are disconnected, each fragment being bounded by thrusts (Thompson, 1991); however, slides are also present, as depicted by Stockton, Thomas, Chapman, and Dykstra (1981, Pl. II, pp. 64–65). The absence of depositional boundaries between lithologies means that normal methods of subsurface prediction break down. Thompson (1991) used thrust slices as structural units and analyzed the subsurface in terms of a "structural stratigraphy" of thrust slices.

The bodies of greenstone and serpentine, although disconnected within and between thrust slices, generally have the largest aspect against surfaces resting on thrusts and slides; therefore, they take on the form of discontinuous tabular bodies. When the fault slices dip steeply, the outcrop has the shape of a narrow lens, as in the northern part of Figure 7. When the fault slices are near horizontal, outcrops are somewhat more rounded and equidimensional, and the boundaries meander in plan without strongly preferred direction, as in the southeastern corner of Figure 7. These general considerations help to define and locate the axis of the Maacama Antiform in the ophiolites of Figure 7. The antiform has an average trend of about N300E. The steamfield lies on the northeast limb of the antiform. Subsurface structural contours by Stockton, Thomas, Chapman, and Dykstra (1981) show a number of smaller parasitic folds on the northeast limb of the antiform, with axial trends in the range N300E to N305E.
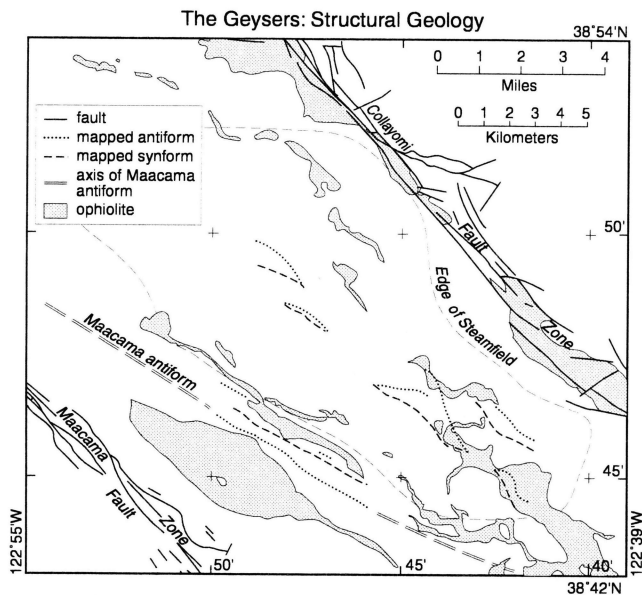
Figure 7: Locality and structural map of The Geysers steamfield. The ophiolite boundaries, Maacama Fault Zone, Collayomi Fault Zone, and Maacama Antiform are from McLaughlin (1978, Sheet 1, and 1981, Fig. 5, p. 12). The antiforms and synforms outside the steamfield are from surface mapping by McLaughlin (ibid.) Those inside the steamfield are derived from subsurface mapping by Stockton, Thomas, Chapman, and Dykstra (1981, Pl. II, pp. 64–65). The steamfield boundary is after Thompson (1991, Fig. 7, p. 63).

Heat flow: Isolines of heat flow through the reservoir overburden are shown in Figure 8. The background values range from 177 to 250 mW/m² (4.2 to 6.0 hfu). The inner values range from 500 to 2,025 mW/m² (12.0 to 48.4 hfu). On the average, the heat flow doubles from 250 to 500 mW/m² (6.0 to 12.0 hfu) in crossing from the surrounding region into the steamfield.

Felsite batholith: The basement rock underlying the steamfield is a buried batholith, with measured ages ranging from 0.9 to 2.4 Ma (Thompson, 1991). Figure 9 shows the shape of the top surface of the batholith. It is an elongated dome that trends to about N305E.

Geometry of the reservoir: The field produces dry steam at 240°C from fractures in Franciscan metagraywacke. A relatively impermeable overburden overlies the perme-
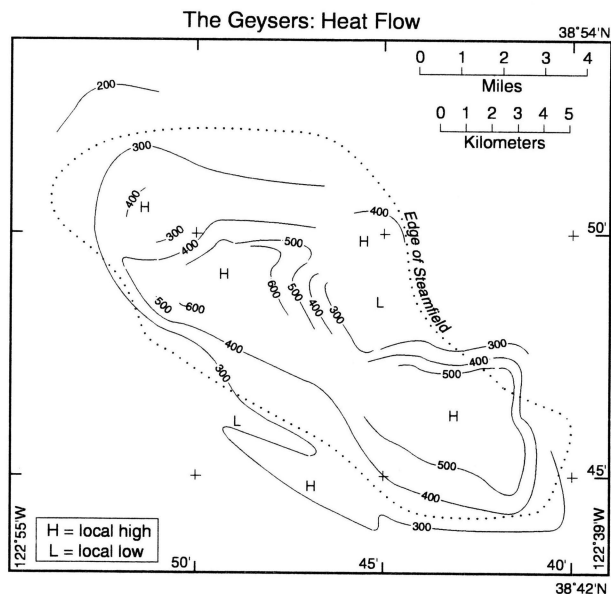
Figure 8: Heat flow at The Geysers steamfield. Contours in mW/m² derived from Thomas (1986, Fig. 5, p. 9). The steamfield boundary is after Thompson (1991, Fig. 7, p. 63).
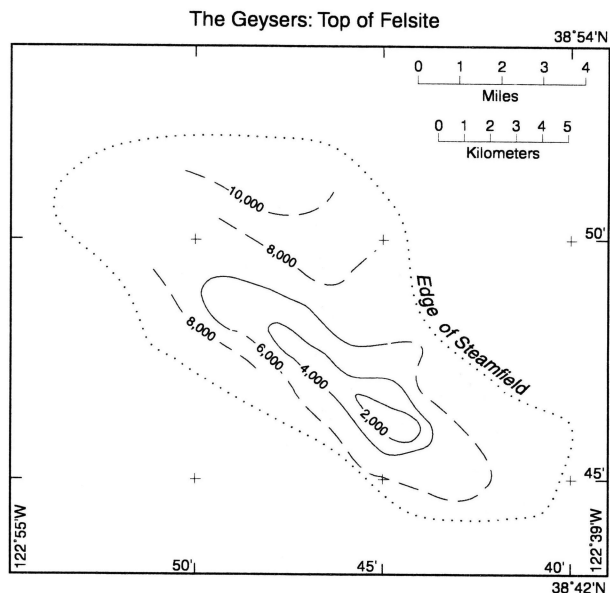
Figure 9: Altitude of the top of the felsite batholith underlying The Geysers steamfield. Generalized contours in feet below sea level and the steamfield boundary are after Thompson (1991, Fig. 7, p. 63).

able rocks of the steamfield. The main resource is typically between 1,219.2 and 3,048 m (4,000 and 10,000 ft) deep. Some wells produce in excess of 37.8 kg/s (300,000 lb/h) of steam (Facca, 1973, p. 2.2). Such production requires a very high fracture permeability.

The steam reservoir was defined by Stockton, Thomas, Chapman, and Dykstra (1981, p. 24) as that region where steam displaces water in rock with a pore volume of about 4.5%. The volume of the reservoir was estimated at 140 km³ by Nathenson and Muffler (1975), 100 km³ by Denlinger (1979), and at 1,167 km³ by Brook, Mariner, Mabey, Swanson, Guffanti, and Muffler (1979).

The upper surface of the reservoir was mapped by logging steam entries in exploration wells. The surface shown in Figure 10 was obtained by Stockton, Thomas, Chapman, and Dykstra (1981, Fig. 4, p. 15) by generalization of a more detailed map (ibid., Pl. IV, pp. 68–69). Another version was provided by Thompson and Gunderson (1992, Fig. 2, p. 66). Figure 10 shows that the upper surface of the reservoir is a dome elongate to azimuth N300E, in general agreement with the trend of Cenozoic folding.
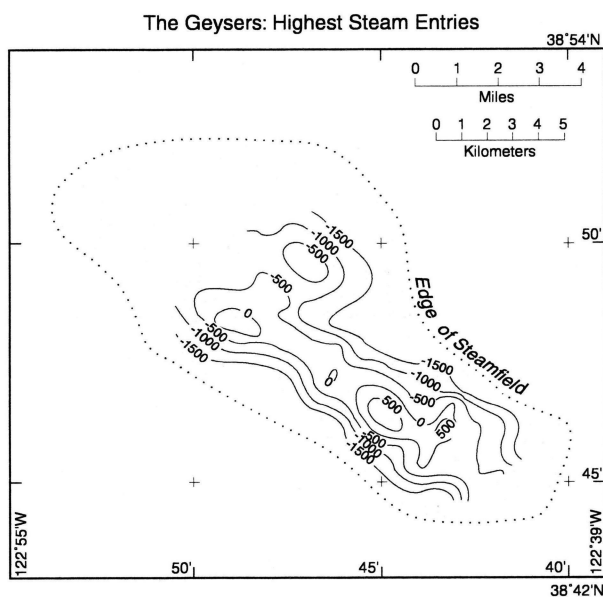
Figure 10: Altitude of highest steam entries at The Geysers steamfield. Generalized contours in feet below sea level, after Stockton, Thomas, Chapman, and Dykstra (1981, Fig. 4, p. 15). The steamfield boundary is after Thompson (1991, Fig. 7, p. 63).

The field was described as an aggregation of five convection cells controlled by the distribution of fracture permeability in Franciscan greywacke (Stockton, Thomas, Chapman, and Dykstra, 1981). The tops of the cells were derived from anomalously shallow first steam entries, which show as highs in the structure contours of Figure 10. From Figures 9 and 10, the average convection cell was found to be about 5 km in diameter. This is about one order of magnitude smaller than The Geysers system as a whole.

Nature of permeability: McLaughlin and Stanley (1976) found the permeability to be related to Cainozoic fault zones trending N325E to N330E. They found an association of hydrothermal alteration, microearthquakes, and resistivity lows with the permeable fault zones.

Thompson and Gunderson (1992) provided evidence that steam-bearing fractures in the greywacke reservoir rock were predominantly horizontal and largely represented structures of Franciscan age, reopened by hydrothermal circulation, which dissolved the calcite cement. The steam-bearing fractures in the underlying felsite were predominantly vertical, aligned in northwest-trending fracture zones, and were thought to be largely cooling fractures formed at less than 2.5 Ma.

A number of origins have been suggested for the huge volume of permeable rock at The Geysers. One explanation is magmatic withdrawal in the felsite underbody, leading to dilitation in the roof rocks. Another explanation is mechanical propping in the massive greywacke, similar to "hang-up" in coal mines with strong roof rocks, which sharply reduces the load on the underlying rocks. Another explanation is that increased pore pressures resulting from magmatic fluids have brought systems of fractures to failure, leading to shear-induced propping of hydraulic fractures.

Grindley and Browne (1976) describe a system of natural hydraulic fracturing in the vicinity of faults induced by accumulation of hydrothermal fluids, a mechanism that is favored for some Nevadan gold deposits.

The steamfield occupies a region of enhanced permeability in the core of the Maacama Antiform trending N305E, which is cored with felsite at depth. The steamfield lies between the Maacama and Collayomi Fault Zones, which are occasionally active dextral transcurrent faults of the San Andreas system. The azimuths of the faults are about N314E and N317E, respectively, averaging about N315E, about ten degrees higher than the azimuth of the Maacama Antiform. The trend of the antiform is similar to that of other folds of the Coast Ranges (Burns, April 1966, Figs. 6 and 8). This suggests that the Maacama Antiform is a ductile structure formed in association with the Cenozoic faults. However, it is not clear how the folding leads to any of the fracturing mechanisms discussed above.

Method of confinement: The reservoir existed because it was confined and leakage of vapor was throttled off. Three methods of fluid confinement were proposed: geological, geochemical, and geophysical.

The "Knoxville" model, for example, attributed to the U.S. Geological Survey (see White, 1966), placed potential steamfields in Franciscan greywacke overlain by a cap of Knoxville Sandstone and Shale, which is relatively impervious to flow across the layering, and would thus constitute a seal.

The "self-sealing" model showed that the steamfield can be self-confining as a result of deposition of hydrothermal minerals at the margins and in the caprock (Facca, 1973). The fluid deposits are silica, carbonates, and sulphates whose solubility decreases with temperature (Facca and Tonani, 1967).

However, recent studies of physically comparable systems in relation to burial of radioactive waste showed that circulating fluid systems could set up toroidal flows for which there was very low leakage at the boundaries. This might be termed a "hydrodynamic trap."

C. Physical Characteristics

Pressure-temperature relations: The upper portion of the reservoir is occupied by steam at a pressure in accord with its temperature. The original condition, before exploitation, was a pressure of 3.4 MPa (500 psi) and a temperature of 243°C (470°F). The reservoir temperature in 1973 was about 250°C to 280°C, and the correlated steam pressure was 3.9 to 6.4 MPa (40 to 65 kg/cm^2)(Facca, 1973, p. 6.5).

The pressure increases with depth at a rate commensurate with saturated steam at maximum enthalpy (White, Muffler, and Truesdell, 1971, Fig. 2, p. 82; Facca, 1973, p. 6.8). A well log in the steam showed that the pressure increased with depth at a rate of 183.4 kPa (1.87 kg/cm^2) for each kilometer of depth; in water the rate was 7.78 MPa (79.3 kg/cm^2) each kilometer (Facca, 1973, p. 6.6).

Circulation system: The steamfield is a two-phase circulation system with steam at about 240°C to 250°C and 3.14 to 3.33 MPa absolute (32 to 34 kg/cm^2) (Facca, 1973, p. 6.12; White, Muffler, and Truesdell, 1971). Steam flows upwards in the larger openings and condenses under the surface cap. Heat is transported upward in the vapor phase to the base of the cap rock, where it is conducted to the surface. The condensate trickles downwards in capillaries and small fissures because of the higher surface tensions of liquid water. Two-phase counterflow convection, consisting of rising steam and descending water, is driven by phase change instability (Schubert and Straus, 1977). Temperature differences control the pressure differences that cause flow.

For a time, the idea of an upper layer of condensate was regarded as physically improbable (Facca, 1973, p. 6.2); however, the physical stability of a near-surface layer of condensate in permeable media was demonstrated by Schubert and Straus (1980).

The steam is of meteoric origin (Facca, 1973, p. 6.8). According to Stockton, Thomas, Chapman, and Dykstra (1981, Fig. 6, p. 19), Cobb Mountain, in the embayment on the northeast side of the steamfield, is the area of recharge, with cold meteoric water descending through the Clear Lake Volcanics to fractures in the underlying rock, thence to recharge the steamfield at depth.

The restricted lateral inflow of water coupled with high heat inflow at the base leads to a vapor-filled reservoir of substantial size (MacMillan, 1970). The required heat flux is of the order of 1 W/m^2 (23 hfu) on the average (Pruess, 1985).

Evolutionary model: Truesdell and White (1973) produced the following evolutionary model of The Geysers. The system initially comprised a water- and steam-filled reservoir, a water-saturated cap rock, and a water- or brine-saturated deep reservoir below a water table. Steam is the dominant, pressure-controlling phase and dominates the large fractures and voids. Water is relatively immobilized in small pores and crevices. With production, the pressure is lowered and the liquid water boils, taking heat from the rock and drying it. After a boiling front develops, the reduced pressure causes increased boiling below the deep water table. Passage of steam through dried rock causes superheating. With continuing exploration, the boiling front descends deeper into the reservoir, and the steam temperature increases.

There are two types of heat pipes. One is liquid-dominated with large liquid saturation and nearly hydrostatic pressure gradient, but another is vapor-dominated with liquid saturation near the irreducible limit and a nearly vapor-static pressure gradient. Pruess (1985) presents reasons why The Geysers might have evolved from liquid- to vapor-dominated because of a short-lived (600-day) fluid mass discharge event. The transition requires a hydrological setting characterized by dual permeability. A high-permeability network of interconnected fractures with small volume provides pressure control, but most of the fluid reserves are stored in liquid form in a porous rock matrix of low permeability. Williamson's (1992) model used a pore volume of 1.13E10 m^3 (0.4E12 ft^3) of which 64% was within the matrix.

D. Geochemical Characteristics

Water chemistry: The surface springs of steamfields, representing condensates, have low rates of discharge. The total for The Geysers is little more than 100 L/min. The waters are strongly acidic, with pH from 2 to 3. The neutral springs are few, but they have very low chloride content, less than 2 mg/L. This is because metallic chlorides, the main vehicle for chlorine in solution, are not carried in the vapor phase. In an area of 30 mi^2 surrounding The Geysers, the surface and ground waters are no higher in chloride than normal cold streams. In general, where surface springs are all low in chloride and subsurface thermal waters are similarly low (<20 mg/L), a vapor-dominated system is indicated (White, Muffler, and Truesdell, 1971).

Water derived from the condensation of steam is very poor in salts and enriched in gases, such as boric acid, ammonia, carbon dioxide, and sulphurated hydrogen (Facca, 1973, p. 6.15).

Steam condensates at The Geysers and steam condensates contaminated with meteoric waters and hydrogen sulphide were recognized as a distinct "water type 1," by Goff, Donnelly,

Thompson, and Hearn (1977). Type 1 waters were undersaturated relative to amorphous silica, low in chloride, low in total dissolved solids, usually contained appreciable sulphate, and had pH as acidic as 1.8.

Mercury deposits: Mercury deposits are associated with The Geysers steamfield, at the Buckman, Big Chief, and Big Injun Mines. Mercury occurs in vapor at The Geysers. White, Muffler, and Truesdell (1971) suggested that vapor-dominated systems provide a mechanism for separating mercury from other metals of lower volatility. Mercury is likely to be enriched in the vapor and might be precipitated in the zone of condensation that surrounds a steam reservoir. This potential association of mercury mines with steamfields became a factor in exploration.

E. Exploration for Steamfields

Target diagnostics: In the search for a repetition of The Geysers, White (1966) lists the following diagnostics: a potent source of heat, such as a magma chamber, at a depth of about 3,048 m (10,000 ft); a reservoir of adequate volume, permeability, and porosity; and an insulating capping of rock of low permeability that inhibits convective loss of fluids and heat. The depth of about 3,048 m (10,000 ft) is necessary to generate sufficient pressure and temperature for the vapor-dominated system to evolve. These diagnostics became important in subsequent geothermal exploration of The Geysers–Clear Lake area.

Facca (1973, p. 9.5) listed four criteria:

(1) a reservoir containing steam in its upper portion;

(2) leakage manifestations at the surface as a result of active faults;

(3) a cap rock resulting from the self-sealing process, partially permeable through the leakage manifestations and active faults, and

(4) a serpentinite structure with allied mercury mines.

Geophysical exploration: Surveys of The Geysers by gravity, magnetic, and electrical methods were regarded by some as not definitive. The principal geophysical technique adopted was mapping the geothermal gradient from patterns of geothermal "gradient" wells. The reasoning was as follows. The depth of the permeability barrier at The Geysers is an important factor controlling the geothermal gradient. The permeable reservoir is about the same temperature everywhere, independent of cap rock geometry. Accordingly, the base of the cap rock is approximately isothermal. It then follows that the geothermal gradient in the cap rock is a function of its thickness. So it was thought that a hidden steamfield might be discoverable by drilling patterns of shallow "gradient" wells, about 100 m deep, before any deep exploratory drilling (Facca, 1973, p. 4.3). This amounts to evaluation of the horizontal derivative of the geothermal gradient, which is the second derivative of the heat flux.

Economic production unit: The minimum power plant size that could be considered by a centralized public power utility in California in 1973 was 100 to 150 MWe, requiring a minimum capacity of 250 to 380 kg/s (2 to 3 million lb/h) of steam. In The Geysers field in 1973, the average production well produced 19 kg/s (150,000 lb/h), from a depth of 1,830 m (6,000 ft), at a drilling cost of $200,000. The price of steam was 3.15 mills/kWh, so the average well generated an income of $189,000 per year. In other words, a well paid for itself in one year. Using that rate of return as a benchmark, a commercial steamfield would comprise 128 wells, spread over about 2.9 km^2 (720 acres). This was the commercial definition of the exploration target in 1973 (Facca, 1973, p. 7.1).

For example, of wells drilled near the eastern margins of the steamfield, the Bianchi No.1 well produced steam at 0.63 kg/s (5,000 lb/h) and was noncommercial (Facca, 1973, p. 6.8). The Cobb Mountain No.1 well found a producing zone 6.7 m (22 ft) thick at a depth of 1,453 m (4,767 ft), and the production rate of 6.3 kg/s (50,000 lb/h) was also subcommercial. However, the Ottoboni well, half a mile away, yielded 25.2 kg/s (200,000 lb/h) and was regarded as a good producer (Facca, 1973, p. 2.4).

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IV. GEOTHERMAL RESOURCES OF THE CLEAR LAKE VOLCANIC FIELD

A. Introduction

The region outside The Geysers steamfield, extending from the Collayomi Fault Zone to Clear Lake, has been the subject of a number of surveys for geothermal resources. Most of this area is underlain by Clear Lake Volcanics, of Quaternary age, and it is convenient to refer to it as the Clear Lake volcanic field, although the geological formation called the Clear Lake Volcanics occurs in scattered outcrops northeast of Clear Lake as far as Chalk Mountain.

There have been multiple, overlapping investigations of the geothermal resources of this region, and ideas that were developed in one program were adopted in others. In order to simplify the discussion, the programs are treated more or less chronologically.

B. Geochemistry of Hot-Water Systems

Hot-water geothermal systems, such as Wairakei, Salton Sea, and Cerro Prieto, have some distinguishing geochemical characteristics (White, Muffler, and Truesdell, 1971).

Hot-water systems have high rates of discharge, typically from several hundred to several thousand L/min. Where near-surface rocks are permeable and the water table is low, the hot water may escape below ground surface, with little or no surface expression. Cold springs are commonly chemically similar to nearby ground water. Warm and hot springs are of two types, neutral-chloride and acid-sulphate.

Hot and near-boiling waters of moderate-to-high discharge rates are high in alkali chlorides, silica, and arsenic. These nearly neutral-to-alkaline-chloride springs are from the main water body, occurring where the water table intersects the ground surface.

Gassy springs of low discharge rate contain generally less than 20 mg/L of chloride; sulphate is the dominant anion; the pH is between 2.5 and 5; and iron, aluminium, calcium, and magnesium are abundant relative to sodium and potassium. These acid springs result from boiling at a low water table. Hydrogen sulphide that evolves with the steam reacts near the surface with atmospheric oxygen to form sulphuric acid, thus accounting for the high sulphate content and low pH characteristic of these waters.

C. A Geochemical "Divide" at the Collayomi Fault and Predictions of Hot-Water Resources in the Clear Lake Volcanic Field

Goff, Donnelly, Thompson, and Hearn (1977) surveyed the Clear Lake volcanic field and found no steam condensate springs or derivative waters northeast of the Collayomi Fault Zone, implying that no steamfields exist in the Clear Lake volcanic field. They did not absolutely exclude steamfields and said that small vapor-dominated systems might exist where local conditions were favorable. However, if they did exist, they would be blind systems; that is, their thermal waters would not reach the surface northeast of the Collayomi Fault Zone.

They found the waters were usually saturated with amorphous silica, were high in chloride, were high in bicarbonate, usually with free carbon dioxide, and low in sulphate. They classified them as their type 2, from hot-water

systems. Their predicted Na-K-Ca reservoir temperatures were about 185°C. An adiabatic quartz-steam model yielded silica reservoir temperatures consistently in the range of 195°C to 210°C. They concluded, in agreement with Donnelly, Hearn, and Goff (1977), that any drillable geothermal system (that is, at a depth of less than 3,500 m) beneath the main Clear Lake volcanic field was probably a hot-water type.

Goff and Donnelly (1978) pointed out that if the Na-K-Ca geothermometer is reliable, then it indicates a geothermal reservoir beneath many square kilometers of land northeast of Clear Lake where there are no springs with temperatures measured above 25°C. They argued that the high Na-K-Ca temperatures obtained from saline springs resulted from leaching of connate fluids from the Great Valley sequence into the thermal waters as they evolved, and by implication, were unreliable indicators of reservoir temperature.

Later, Donnelly, Goff, and Nehring (1979) used chemical analyses of spring waters to predict the extent of the outer limits of the hot-water geothermal area beyond the confines of the Clear Lake volcanic field (Figure 11).

The conditions in liquid brine underlying The Geysers steamfield were described by Truesdell and White (1973). Gennis, Blades, Niimi, and Fisher (1984) suggested that outside the boundaries of the steamfield, the Clear Lake volcanic field was underlain at a depth of 3,660 to 4,570 m (12,000 to 15,000 ft), by a liquid-dominated, hot-water system comprising high-pressure, high-temperature geothermal brine. This resource was probably at hydrostatic pressure, 27.6 to 34.5 MPa at 3,050 m (4,000 to 5,000 psi at 10,000 ft), and high temperature, 200°C to 300°C (400°F to 600°F). It would have potential for electric power generation.

Wright (1991) cited Goff, Donnelly, Thompson, and Hearn (1977) for the concept of an extensive hot-water resource at temperatures greater than 200°C underlying a large area northeast of the steamfield to Clear Lake and beyond.

Goff, Donnelly, Thompson, and Hearn (1977) said that large areas of the volcanic field are probably underlain by Franciscan rocks that commonly have low permeability, so economic quantities of hot water at drillable depths (then less than 3,500 m) may not be easily extracted unless the wells are drilled close to fault zones where fractured rocks allow thermal waters to move freely upward.
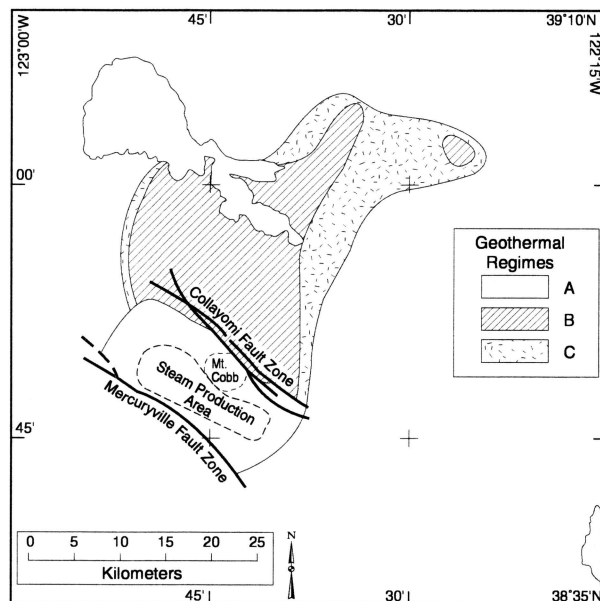
Figure 11: Approximate inferred limits of vapor-dominated and hot-water-dominated areas in The Geysers–Clear Lake area. Area "A" is the vapor-dominated area, "B" is the "realistic" hot-water area, and "C" is the maximum possible extent of the hot-water area. After Donnelly, Goff, and Nehring (1979, Fig. 3, p. 353), see also Goff, Donnelly, Thompson, and Hearn (1977, Fig. 5, p. 514) and Donnelly, Goff, Thompson, and Hearn (1978, Fig. 1, p. 101).

D. Geothermal Resources of Big Valley

The Division of Mines and Geology conducted a series of investigations of hot-water geothermal resources of the Sonoma Valley area, south of The Geysers (Youngs, Chapman, Chase, Bezore, and Majmundar, 1983; Youngs, Campion, Chapman, Higgins, Leivas, Chase, and Bezore, 1983; Campion, Bacon, Chapman, Chase, and Youngs, 1984) and of the Big Valley area near Kelseyville (Youngs, Kishi, and Campion, 1983).

The Big Valley is a wide, shallow topographic basin extending north from Kelseyville to Clear Lake. It is bounded on the west by Franciscan rocks of the Mayacmas Mountains and on the east by the volcanic edifice of Mt. Konocti. There is a variety of basement rocks, which are overlain by Holocene and late Pleistocene lacustrine sediments (Sims, Rymer, and Perkins, 1988, Fig. 10, p. 41).

At least 37 low-temperature geothermal wells and springs were located in The Big Valley area, mostly within 7.5 km of Kelseyville. Temperatures were in the range from 20°C to 46°C. The average temperature was 23°C on alluvium, 25°C on Cache Formation, and 37°C for wells sited on Clear Lake Volcanics. The Na-K-Ca geothermometer was found to be greater than 400°C at Little Borax Lake, northeast of Mt. Konocti, declining to 100°C on the western side of the mountain. The Big Valley Fault was found to be a hydrological barrier, and all the warm wells were located south of the fault.

Youngs, Kishi, and Campion (1983) concluded that the low-temperature resource of Big Valley was a liquid-dominated hydrothermal convection system. They envisaged the circulation system as faults in the basement providing conduits for ascending warmed meteoric fluids to flow into permeable aquifers. The source rocks were thought to be Cache Formation and interfingering Clear Lake Volcanics.

A composite temperature profile based on 40 wells is illustrated in Figure 12. The straight line of best fit is 102 mK/m, which is interpreted as the geothermal gradient in the basement. The scatter is interpreted as having been caused by circulation. The system is interpreted as a convectively disturbed conductive regime, similar to the Otway and Artesian Basins (Burns, Creelman, Buckingham, and Harrington, 1995), and the scatter indicates the height range of circulation. In that event, the waters were not necessarily resurgent from fault zones but could have been waters heated conductively while within the aquifers.
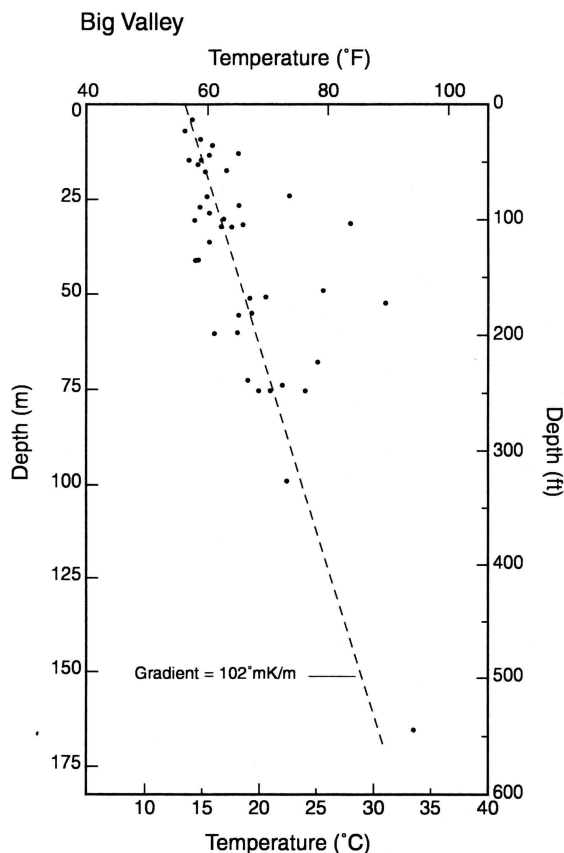
Figure 12: Temperature versus depth, Big Valley area. Scatter diagram of maximum recorded temperature versus depth of recording for 41 selected wells in the Big Valley area, California. From Youngs, Kishi, and Campion (1983, Fig. 1, p. 16).

E. Geothermal Resources of Lake County

In 1983, Lake County received money from the California Energy Commission's Geothermal Development Grant Program for Local Governments to determine the extent of moderate-temperature geothermal resources. Gennis, Blaydes, Niimi, and Fisher (1984) envisaged a two-tier geothermal resource in the County. The first tier was deep, comprising the vapor-dominated steamfield and a liquid-dominated hot-water resource. The second tier was shallow and low temperature.

In the Clear Lake volcanic field, it was supposed that deep hydrothermal fluids would be able to migrate upward in faulted areas. There they would mix with meteoric waters to produce a secondary hydrothermal resource at low temperature. This resource would occur at depths of 305 to 610 m (1,000 to 2,000 ft), with waters at temperatures variously estimated at 65°C to 120°C and 50°C to 90°C. The average system would be 66°C at 457 m. Water pressures would be subartesian. The resources would be suitable for direct-use geothermal projects and possibly for small-scale power production. It would be manifest at the surface as numerous hot and warm springs.

Tapping the low-temperature shallow resource for direct-use applications would require finding and drilling into fault structures near the surface, or into shallow permeable aquifers being charged by hot geothermal water from depth. These were very localized, site-specific targets. For direct-use purposes, 8 ha (20 acres) is a large area, so exploration techniques would have to be oriented toward small areas and detailed interpretations.

In order to evaluate the low-temperature resource, Gennis, Blaydes, Niimi, and Fisher (1984) compiled a map of estimated temperatures at a depth of 610 m (2,000 ft), as shown in Figure 13.
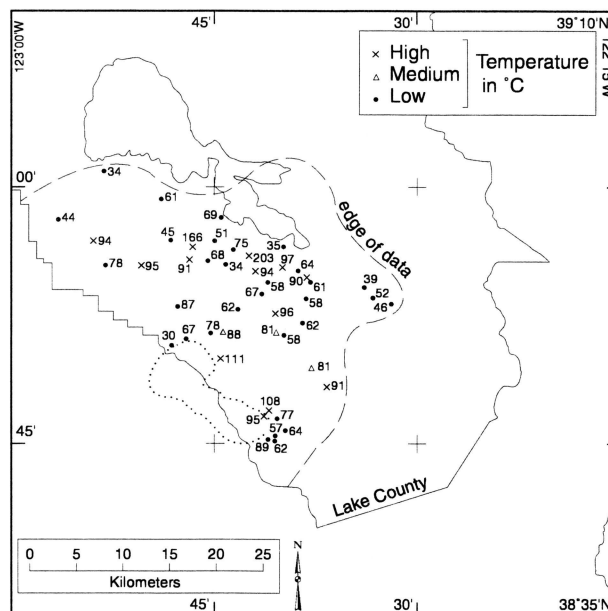
Figure 13: Temperatures at a depth of 610 m (2,000 ft), Lake County. Indicated by different symbols are temperatures considered low (30°C to 78°C), medium (81°C to 89°C), and high (94°C to 203°C). From Gennis, Blaydes, Niimi, and Fisher (1984, Fig. 9, p. 23).

Consistent with the hydrothermal model, an exploration target was developed. Their target for direct-use geothermal fluid was an aquifer comprising several hundred feet of graywacke, within a depth of 300 to 600 m, penetrated by faults. Waters were expected to have temperatures of 65°C to 120°C. Wells would probably be subartesian.

The targeting method was to intersect three data layers as follows:

(1) faults with surface expression, including hydrothermal alteration, derived from geological maps;

(2) faults at depth, inferred from micro-earthquake hypocenters (Bufe, Pfluke, Lester, and Marks, 1976) (these faults may be active); and

(3) indications of abnormal heat flow, such as temperature greater than 90°C at a depth of 610 m (2,000 ft), using a zone of influence of 610 m (2,000 ft).

The results of the map analysis are shown in Figure 14. In general, the highlighted areas "A" and "B" in Figure 14 have good heat flow and are near permeable fault zones. The areas of excellent potential ("A") have a combination of highly favorable factors, such as faults or high temperature. The areas of good potential ("B"), have at least one highly favorable factor.
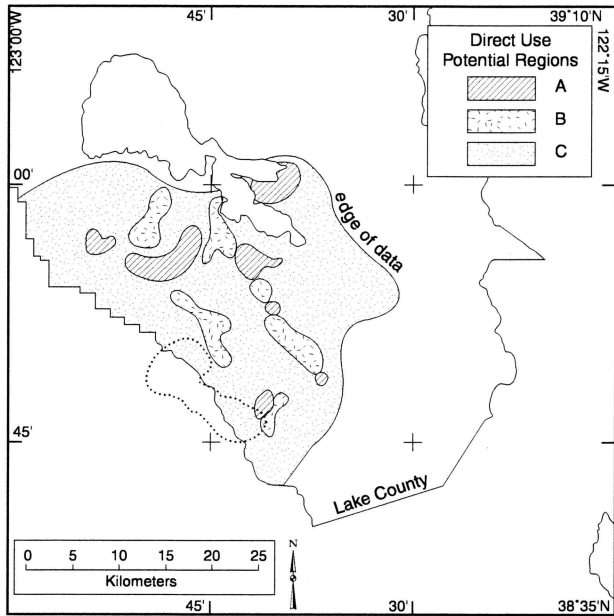
Figure 14: Map of Lake County showing areas with geothermal direct-use potential. The regions are "A," excellent potential; "B," good potential; and "C," unclassified potential. The outer heavy line shows the limit of data. Based on Gennis, Blaydes, Niimi, and Fisher (1984, Pl. 14). The boundary of The Geysers steamfield is shown by a dotted line, from the California Division of Oil and Gas (1984).

F. Geothermal Development at Ag Park

The Sulphur Mound Mine property is on Highway 29 due south of Mt. Konocti, on the western edge of the moat surrounding the peak called the Sugarloaf. Geothermal resources with temperatures of 49°C to 54°C (120°F to 130°F) had been found nearby in fractured obsidian at a depth of about 91.4 m (300 ft), under a cover of about 12.2 m (40 ft) of alluvium. In 1984, the California Energy

Commission awarded funds to Lake County, in conjunction with Mendocino-Lake College, to develop a Geo-Ag Heat Center at the site, at which the college would demonstrate the agricultural potential of the geothermal fluid. The first well was completed on January 26, 1986. It intersected a hot-water plume at a depth of about 215 ft (Figure 15). The demonstration was successful, and in 1992 the center was transferred to a private corporation for commercial operation.
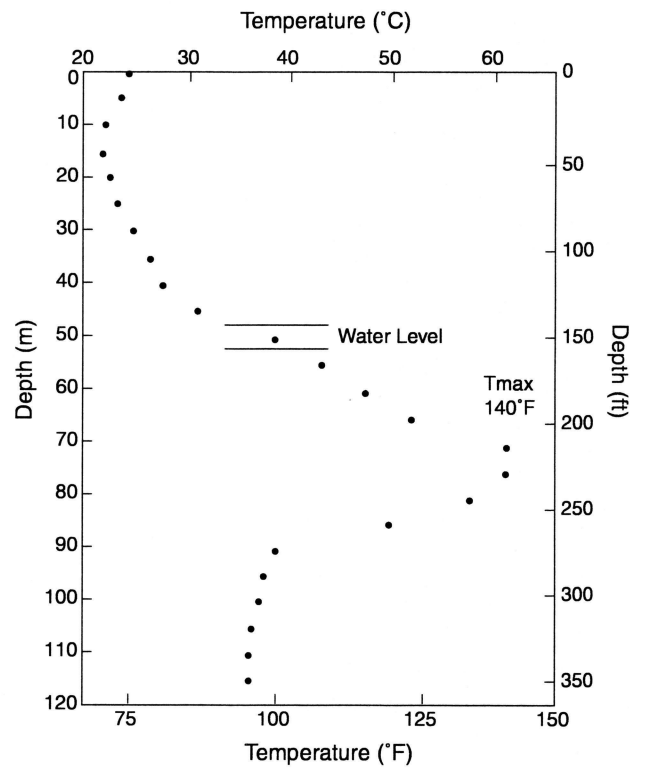
Figure 15: Temperature log for Ag Park Well No.1. The maximum temperature is 60°C at a depth of 70 m. From the records of the California Division of Oil and Gas.

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G. Lake County General Plan

In May 1989, the Board of Supervisors for Lake County added a geothermal resource and transmission element (GRTE) to the Lake County general plan (Hinds, Dellinger, Graham, and Seidler, 1989). The GRTE was zoned according to the probable geothermal regime (Figure 16). The zonation was intended as a generalized illustration of resource areas, not as a technical geologic map of geothermal resources. The "reservoirs" in Figure 16 were defined as follows.

(A) Known vapor-dominated reservoir: Within this area, commercial high-temperature steam production is highly probable, based upon current economics associated with drilling and fluid recovery. A greater percentage of wells drilled within this boundary are expected to be productive.

(B) Unproven vapor-dominated reservoir: The development of this area for high-temperature steam production, based on current economics, has proven to be of limited success. Improvements in geothermal-related technologies may reduce costs and make this area economically feasible for commercial production. Further exploration in the extreme portions of this area, particularly to the northwest, is necessary to determine the area's ultimate potential.

(C) Probable liquid-dominated reservoir: Evidence suggests that the potential for high-temperature, hot-water and shallow, low-temperature resources is good in this area.

(D) Probable low-temperature, shallow reservoir: Good potential for direct-use applications exist within this area. There is also the possibility of a limited, deep, high-temperature hot-water resource in areas adjacent to the unproven vapor-dominated and probable liquid-dominated reservoirs. Local geologic conditions may also present the opportunity for high-temperature, hot-water development throughout portions of this area.

(E) Potential low-temperature and possible high-temperature, hot-water reservoir: This area is in close proximity to the Wilbur Springs geothermal area, which is known to contain a reservoir suitable for high- to low-temperature development of hot water. The boundary shown in Figure 16 is very speculative because of the absence of exploration data in this area.
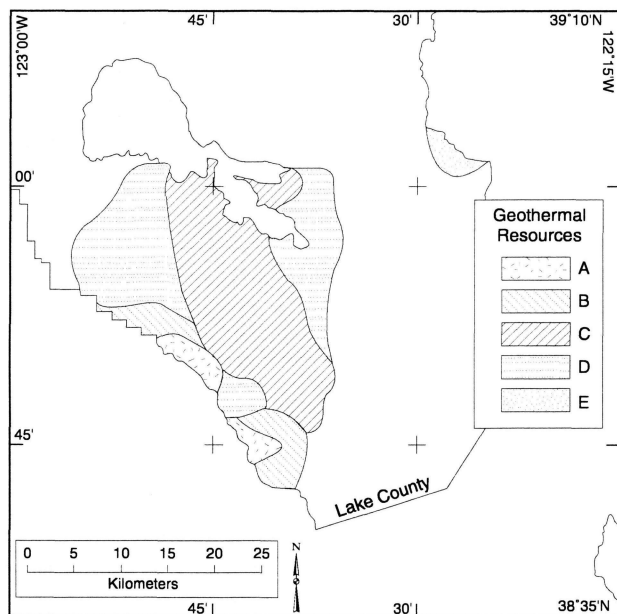
Figure 16: Resource type and reservoir areas of Lake County. For explanation of regions "A" to "E," see text. From Hinds, Dellinger, Graham, and Seidler (1989, Vol. 1, Fig. 2.1, pp. 2–9).

H. The SE Geysers Effluent Pipeline and Injection Project

Research activity at county level up to 1989 was primarily confined to broad geothermal potential and hot-water development. However, The Geysers steamfield is an important source of revenue to the county. The SE Geysers effluent pipeline and injection project is an innovative new development that aims to maximize that return by prolonging the life of the steamfield.

Since this report was drafted, a pipeline carrying wastewater from the City of Clearlake for reinjection into the SE Geysers has become a reality (Dellinger, 1993). Earlier reports regarding the geothermal use of wastewater are Burns and Potter (1990) and Goddard and Goddard (1991).

The pipeline will carry 221 L/s (3,500 gal./min) of treated wastewater from two Lake County effluent treatment plants through a 26-mile, (0.51-m), 20-in.-diam pipeline to the southeast part of The Geysers steamfield. There, two geothermal operators will distribute the effluent to injection wells. Five power plants are expected to benefit from the additional steam supplies created by the effluent injection. There is expected to be a net gain of 20 to 50 MWe in power plant capacity, equating to 280,000 MWhe of electricity generation annually.

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V. GEOTHERMAL EXPLORATION AT BORAX LAKE

A. Introduction

The geothermal industry conducted an exploration program for systems that could be developed as steamfields. Exploration started near The Geysers and progressively "stepped out" toward the northeast. The more important wells have been described previously (Walters and Coombs, 1989, 1992; Burns and Potter, 1990; Burns, August, 1996). Locations are shown in Figure 17.

The exploration target at Borax Lake was developed from a number of lines of evidence. These were evidence of high subsurface temperatures provided by the geochemistry of thermal waters; evidence of low permeability provided by fossil hydrothermal systems, geological associations, and electrical resistivity; and evidence of high heat flow provided by irrigation and domestic water wells. The exploration program drilled a triplet of shallow wells to confirm the existence of high geothermal gradients and then the deep exploration well named "Borax Lake 7-1."
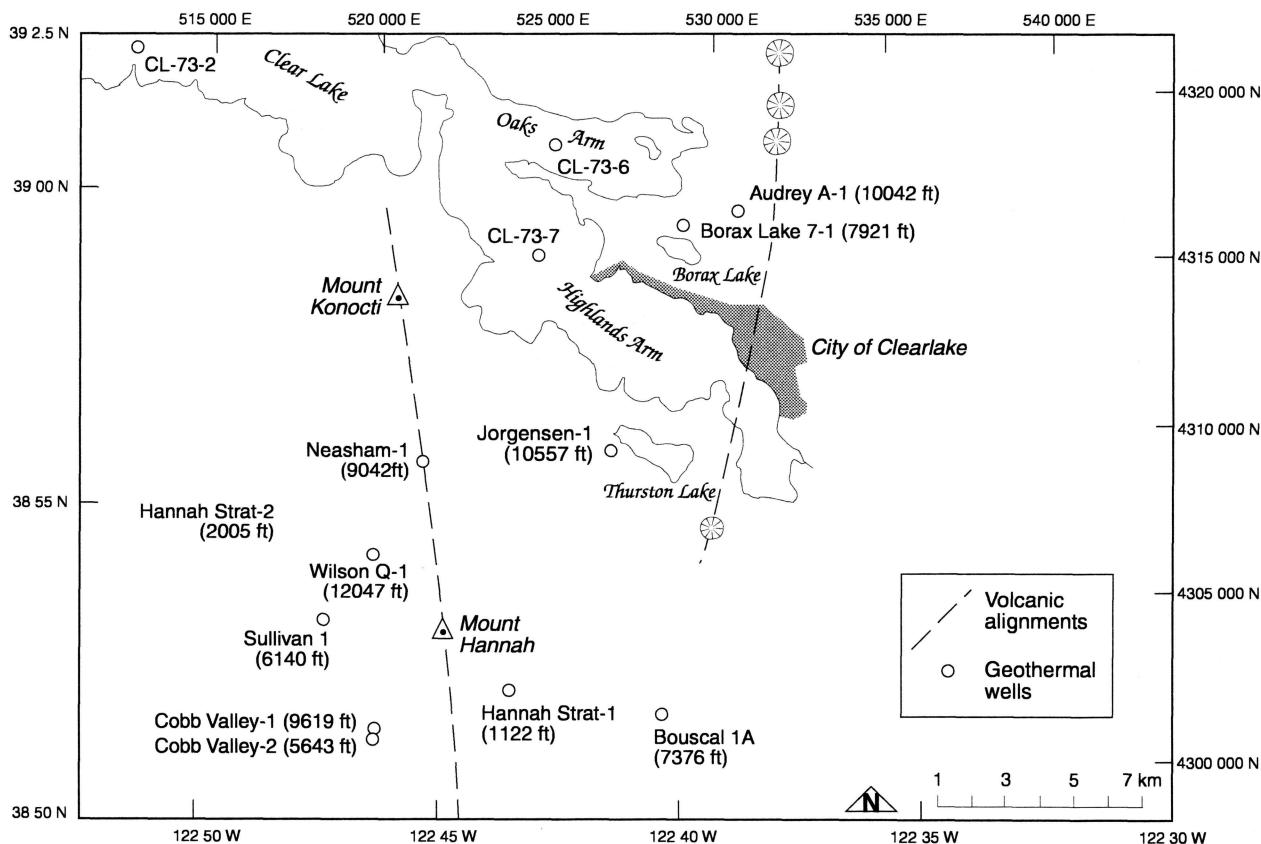
Figure 17: Deep exploration wells in the vicinity of the Borax Lake. From Burns (August 1996, Fig. 2, p. 5).

B. Geochemistry of Thermal Waters

Geochemical "divide" at Stoney Creek Fault: The Coast Ranges are bounded on the east by the Central Valley of California. The junction of these two topographic and geological provinces is marked, approximately, by the Stoney Creek Fault. There is a regional change from choride-rich waters in the Great Valley sequence rocks of the Central Valley on the east, to bicarbonate-rich water in the Franciscan rocks of the Coast Ranges on the west, with mixed waters in the vicinity of the boundary (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973). The methane-to-carbon-dioxide ratio is highest east of the Stony Creek Fault; to the west, the ratio is reversed.

Geochemical traverse across the Coast Ranges: A traverse across the Coast ranges encountered a series of representative geothermal waters. From east to west, these were an oil exploration well named the Wilbur oil test, then Wilbur Hot Springs, Elgin Mercury Mine, Abbott Mercury Mine, Grizzly Spring, Sulphur Bank Mine, Seigler Hot Springs, The Geysers, and finally Skaggs Hot Springs. Locations are shown in Figure 1. Some chemical analyses available at the time are given in Table 1.

The Wilbur oil test well was drilled into the eastward-dipping homoclinal sequence of Great Valley rocks on the eastern side of the Coast Ranges (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A10). It found an oil-field brine, high in sodium chloride (Table 1). The Wilbur oil test waters were classified as "high-chloride, connate" waters by White, Barnes, and O'Neil (1973) and Beall (1985).

The Wilbur Springs and Elgin Mine waters were derived from a common source. The fluid probably contained about 12,000 mg/L of chloride at depth. The composition of the waters (analyses, Table 1) was explained by the addition of ammonia, carbon dioxide, and boron to the Wilbur oil-test water (White, Barnes, and O'Neil, 1973).

The name "Sulphur Creek group" at Wilbur Springs (Table 1) referred to three small mercury mines. The mine springs yielded high-chloride hot waters similar to those at Wilbur Springs. The rate of discharge was 400 to 500 L/min (White 1967).

The Abbott Mine was notable for the association of mercury mineralization and oil. The commercial mercury deposit at the Abbott Mine was confined to depths of less than 182.9 m (600 ft) The "froth veins" contained spherical shells of opal filled with oil, which were formed at an interface between a hydrous liquid and immiscible droplets of oil. The shells contained cinnabar, indicating that the hydrous fluid was transporting and depositing mercury. Gaseous, solid, and liquid hydrocarbons were abundant in the mine. Hot saline waters discharged from the lowest tunnel of the mine at 75 to 100 L/min. The water (Table 1) was high in bicarbonate, chorine, and boron. The water also showed a high ratio of magnesium to calcium because of the proximity of serpentine and an enrichment in sulphates resulting from acid mine drainage (White, 1967).

The waters of Abbott Mine and Grizzly Spring (analyses, Table 1) were explained by meteoric dilution of deep water approximately intermediate in chloride content between Wilbur Springs and Sulphur Bank waters. It was suggested that deep upflowing intermediate-chloride waters were erratically enriched in combined carbon dioxide, boron, and ammonia (White, Barnes, and O'Neil, 1973; Beall, 1985). The waters were classified as "partly connate, modified by metamorphic reactions" (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A12).

No.	Name	Temp. (°C)	pH	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	B (mg/L)	HCO₃ (mg/L)	H₂S (mg/L)	NH₄ (mg/L)	SiO₂ (mg/L)	SO₄ (mg/L)	Na-K-Ca (β)	(°C)	Qch (°C)	Qst (°C)
1	Skaggs Spring	54	7.2	879	9.8	26	61	60	---	---	---	---	151	26	1/3	104	138	153
2	The Geysers	100	1.8	130	2.1	35	33	---	---	---	---	---	75	795	4/3	43	93	120
3	Seigler Spring	38	---	272	51	22	75	336	---	---	---	---	180	20	1/3	226	151	162
4	Mazolla well	42	7.2	83	5	58	53	36	4	582	---	1	308	4	4/3	53	196	194
5	Konocti well	43	7.8	177	10	9	123	65	17	1110	---	3	300	5	1/3	159	193	192
6	Soda Bay			1722	12	92									1/3	88	---	---
7	SBM spring	69.4	6.8	1190	23	20	55	644	620	3290	12	464	42	598	1/3	132	44	96
8	SBM spring	77	7.5	1100	33	7	22	690	660	2960	4	476	72	454	1/3	160	91	118
9	SBM Hermann	--	---	1706	25	21	5.5	693	---	---	4.6	24	37	17	1/3	125	57	91
10	SBM Parrot	--	---	1320	39	20	1.6	667	---	---	1	1.1	42	466	1/3	153	63	96
11	Grizzly Spring	18	7.2	2720	53	135	712	3940	178	4490	---	1.7	56	4.8	1/3	131	78	107
12	Abbot Mine	26.1	7.1	1500	39	64	443	1900	56	2710	1	22	16	467	1/3	140	23	62
13	Elgin Mine	68.5	7.4	9110	506	5.9	29	11000	240	7240	170	243	244	6.8	1/3	238	175	180
14	Wilbur Spring	55	6.87	8500	440	2.8	38	9700	310	7130	190	280	200	390	1/3	240	130	168
15	Wilbur Spring	57	7.2	9140	460	1.4	58	11000	292	7390	178	303	190	23	1/3	248	155	165
16	Wilbur oil test	cold	8.60	6700	55	580	92	11400	23	62	23	17	0.5	72	1/3	99	OOR	OOR

Table 1: Chemical analyses of geothermal waters of The Geysers–Clear Lake area. Locations are shown in Figure 1. All measures are metric. Geothermometers after Fournier (1977). OOR = out of range.

1. Skaggs Hot Springs. Analyst Winslow Anderson, 1888. From Waring (1915, p. 81) and White (1957b, p. 1676).

2. The Geysers. Witches Cauldron Spring. Analyst unknown. From Waring (1915, p. 97).

3. Seigler Hot Springs. Iron Spring No. 3. Analyst unknown. From Waring (1915, p. 97).

4–6. Mazzola (or Mazolla) well, Konocti Inn well, and Soda Bay spring. From Zimmerman (1975c, Tab. II).

7. Sulphur Bank Mine. "Geyser spring." Analyst C. E. Roberson, March 26, 1957. From White and Roberson (1962, Tab. 1 pp. 412–413). Also "Borax Springs" in Berkstresser (1968, App. A, p. 20; App. B, p. 38).

8. Sulphur Bank Mine spring. From Zimmerman (1975c, Tab. II).

9–10. Sulphur Bank Mine, Hermann shaft and Parrot shaft. Analyst W. H. Melville, c.1884. From Waring (1915, p. 98) after Van Winkle and Eaton (1910).

11. Grizzly Spring. Analyst C. E. Roberson, March 27, 1957. From Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973, Tab. 2, pp. A10–A11) and White, Barnes, and O'Neil (1973, Tab. 1, p. 549).

12. Abbot Mine. Reardon tunnel. Analyst C. E. Roberson, March 27, 1957. From Berkstresser (1968, App. A, p. 21; App. B, p. 38, SiO₂ = 16), after White, Hem, and Waring (1963).

13. Elgin Mine. Northwest spring. Analyst C. E. Roberson, June 7, 1955. From White, Barnes, and O'Neil (1973, Tab. 1, p. 549).

14. Wilbur Hot Springs. "Main" spring. Analyst J. Rapp, December 2, 1969. From Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973, Tab. 2, pp. A10–A11) and White, Barnes, and O'Neil (1973, Tab. 1, p. 549).

15. Wilbur Hot Springs. "Sulphur Creek group." Analyst W. W. Brannock. From Barnes, (1979, Tab. 13.1, pp. 580–581) after White, Hem, and Waring (1963, Tab. 15).

16. Wilbur Springs "oil test." Analyst J. Rapp, March 19, 1970. from White, Barnes, and O'Neil (1973, Tab. 1, p. 549).

The Sulphur Bank Mine waters (Table 1) were very high in ammonia and boron, and relatively high in carbon dioxide and iodide relative to chloride. The ammonia content of 460 mg/L was near the maximum that has been recorded in natural systems. The boron content of 620 mg/L was nearly equal to chlorine and is exceeded by only a few natural waters world-wide. The total natural rate of discharge, calculated to a chloride content of 640 mg/L, was about 200 L/min (White, 1967).

The Sulphur Bank Mine waters were isotopically similar to Wilbur Springs but chemically were classified with the bicarbonate waters of Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973) and are described as "low-chloride metamorphic" waters, the product of progressive metamorphism of marine sediments, by Beall (1985).

Waters at Seigler Hot Springs were much richer in bicarbonate than chloride (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A12). The isotope studies of White, Barnes, and O'Neil (1973) found the waters to be entirely of meteoric origin (Table 1).

In the western part of the Mayacmas district, thermal activity occurs at the surface at The Geysers, the Little Geysers, and the Sulphur Bank area of The Geysers. The hot springs were surficial condensates of steam, diluted with meteoric water (White, 1967). The steam was dry; that is, it did not entrain water, so nonvolatile cations were quite low (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A12). The pH was low, the sulphate (from oxidation of hydrogen sulphide) was high, and although not shown in this analysis (Table 1), chloride was almost absent. The total discharge was a few liters a minute or less. The waters were identified as surficial condensates of steam, diluted with meteoric water (White, 1967).

Skaggs Hot Springs were in coastal-belt rocks, and the fluids were intermediate in character between the Franciscan and Great Valley sequence rocks (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A13). The springs occurred near the Skaggs Springs mercury mine, where methane was encountered in the underground workings. Although not shown in the analysis (Table 1), the springs were exceptionally high in bicarbonate and boron relative to chloride, but hydrogen sulphide was low. White (1967) reported that Everhart observed waters depositing mercury minerals in 1950. Total discharge from the three springs was about 100 L/min (White, 1967).

Connate waters: The waters found in the Wilbur oil test, east of the Stoney Creek Fault, were drawn from the sediments of the Great Valley Sequence. They were chemically and isotopically similar to the oil-field waters of the Central Valley of California, only a few miles to the east, and to other oil fields of California. The waters may be described as connate, and are due to fossil seawater being expelled from marine sediments by compaction, with source pressures higher than hydrostatic. High chloride waters at Skaggs Springs on the western side of The Geysers may be from the same source.

Vapor phase of deep origin: One model that explained the aqueous geochemistry at Wilbur Springs was that a high-chloride connate water, drawn from shallow depth in the Great Valley Sequence, was enriched in carbonate, ammonia, and boric acid by the addition of vapor with very little liquid water and drawn from deep sources. The HCO_3/Cl and B/Cl ratios tended to increase rather erratically from east to west throughout the region, presumably because the proportion of vapor added to the total fluid increased erratically westward (White, Barnes, and O'Neil, 1973). If this

model were correct, then the widespread occurrence of this enrichment would imply that "a vast region between The Geysers and Wilbur Springs . . . (might be) . . . underlain by some sort of reservoir leaking out steam" (Tonani, 1973). However, Clear Lake waters did not show a correlation of boron with chlorine content; instead, the B/Cl ratio varies from locality to locality, indicating isolated reservoirs, and in particular, separate reservoirs at Wilbur Springs and Sulphur Bank Mine (Goff, Adams, Trujillo, Counce, and Mansfield, 1993).

The Sulphur Bank Mine waters were not explained by the model. The dominant fluid seemed to be a low-chloride liquid phase of deep origin, accompanied by a carbon dioxide–rich vapor. The physical situation at the mine appeared to rule out a high proportion of steam in the vapor phase (see also Burns, Potter, and Zyvoloski, 1992). It was concluded that the Sulphur Bank Mine waters were waters of the low-chloride type accompanied by a carbon dioxide–rich vapor (White, Barnes, and O'Neil, 1973; Beall, 1985).

The low-chloride source waters may have been accompanied by a carbon dioxide–rich vapor (White, Barnes, and O'Neil, 1973; Beall, 1985). Elsewhere in the Coast Ranges, a similar vapor may have been the dominant or even the only fluid phase of deep origin (White, Barnes, and O'Neil, 1973; Beall, 1985). An isotope study of geothermal gases, made in the course of this project, showed that the gases were not drawn from a widespread high-temperature geothermal reservoir. Instead, the gases were of crustal origin, perhaps with magmatic influences in places, which mixed near the surface with air and air-laden groundwater (Goff, Adams, Trujillo, Counce, and Mansfield, 1993).

Franciscan waters: In an acclaimed study, White, Barnes, and O'Neil (1973) found that isotope geochemistry indicated three water types, mixtures of which explained the geochemistry of waters issuing from Franciscan rocks. The first type was meteoric water, in which deuterium and oxygen-18 vary with distance from the coastline in accordance with the linear trend of Craig (1961), $\delta D = 10 + 8 \times \delta^{18}O$.

The second type was connate water of the Wilbur Springs group, with B/Cl = 0.02. The third type was metamorphic water, a variety of connate water, of the Sulphur Bank Mine group, with B/Cl = 0.98. The high- and low-chloride connate waters have similar average isotope ratios, with $\delta D = -22.99$ ‰, and $\delta^{18}O = 4.77$ ‰ (Goff, Adams, Trujillo, Counce, and Mansfield, 1993, Fig. 2, p. 4).

With the exception of the steam condensate waters at The Geysers, most of the waters in the region fit a mixing trend between meteoric and connate water. This indicates that connate water, driven out under pressure, is mixing with meteoric water as it ascends. Variations in boron and ammonia are therefore a result of variations in the connate source, and in carbon dioxide, variations are caused by proximity to magmatism. Many other thermal and mineral waters in the northern California Coast Ranges and inland as much as 150 km are similar to one of these two types or to gradations between the two (White, Barnes, and O'Neil, 1973).

This mixing trend was the alternative model to a vapor phase of deep origin. It implies that there is no large geothermal reservoir underlying the Clear Lake region, but that instead, the waters issue from small, localized reservoirs (Goff, Adams, Trujillo, Counce, and Mansfield, 1993).

C. Fossil Hydrothermal Systems

Several geological occurrences were taken as evidence of fossil hydrothermal activity. These were the occurrence of serpentine, silica-carbonate rock, mercury mineral deposits, and hydrothermal alteration. There seemed to be an association of serpentinite with many of the highly productive mercury deposits of the Coast Range, with many hot springs, and with The Geysers geothermal field (Facca, 1973, p. 2.8).

Serpentinites: "Serpentine structures," or "piercement structures," were essentially ovate areas of Franciscan or younger rocks, intruded by serpentinite. The name derives from serpentine piercement structures in the Alps (Facca, 1973, p. 1.3). The reasoning seems to have been that if the serpentinization were induced by hydration, then the occurrence of a serpentinite structure was indicative of permeability in the adjoining greywacke.

Silica-carbonate alteration: The occurrence of this rock was taken as an indication of past geothermal activity resulting from deeply circulating meteoric waters since the late Miocene (Facca, 1973, p. 2.13). Silica-carbonate rocks were usually found at graywacke-serpentinite contacts, or in sheared areas along major faults (Facca, 1973, p. 2.13).

Mercury mineralization: Vapor-dominated systems were thought to provide a good mechanism for separating mercury from other metals of lower volatility. Mercury was likely to be enriched in the vapor of these systems, and the surrounding zone of condensation favored the precipitation of cinnabar (White, Muffler, and Truesdell, 1971). Accordingly, the existence of mercury deposits might indicate previous episodes of steam emission and would be a favorable indicator for prospecting.

Many of the mercury mines in the ranges discharged bicarbonate-rich solutions that were shown to alter serpentinite to silica-carbonate rock. This led to the hypothesis that the bicarbonate-rich fluids may be related to the mercury ore–forming fluid (Barnes, Hinkle, Rapp, Heropoulos, and Vaughn, 1973, p. A1). However, White and Roberson (1962) and Barnes, Hinkle, Rapp, Heropoulus, and Vaughn (1973, p. A17) thought that the bicarbonate-rich waters in the Franciscan rocks of the Coast Ranges, although causing silica-carbonate wall-rock alteration in the serpentines, were not capable of forming commercial mercury deposits.

Evidence of fossil hydrothermal activity is provided in geothermal regions by deposits of sinter or travertine and areas of acid leaching. The acid leaching occurs when hydrogen sulphide oxidizes at the surface to form sulphuric acid (White, Muffler, and Truesdell, 1971). Some fossil hydrothermal activity was very recent, as shown at The Geysers, where hydrothermal alteration crosscuts Quaternary landslides (McLaughlin, 1981, Fig. 10, p. 19).

The serpentinization is probably mid-Tertiary and is probably not indicative of modern hydrothermal systems. Permeability in greywacke can be reduced by sealing or increased by dissolution of older fracture fillings. The evidence that a greywacke was once permeable may not be relevant to the present time. Mercury deposits are potentially more relevant because some hot springs carry mercury at the present time. Hydrothermal alteration is the best evidence of systems that have recently stopped flowing. There is evidence that the Sulphur Bank Mine spring has been flowing for over 30 ka (30,000 yr) (Sims and White, 1981, Fig. 117, p. 239), and we may take that as an indication of the life span of a hot spring. Fossil hydrothermal alteration then indicates a system that was abandoned on about that time scale and is probably relevant to the present plumbing.

D. Geophysical Signatures

Gravity, magnetic, electrical, and seismic surveys were conducted across The Geysers–Clear Lake area, and the results were reviewed by Chapman (1975) and Isherwood (1976, 1981).

The residual gravity showed a low of about 6 mgal over the producing steamfield (Isherwood, 1981, Fig. 39, p. 84). The magnetics showed a high over the Collayomi Fault Zone, attributed to serpentine. However, in general, trials of gravity, seismic, magnetic, electrical, infrared, and microseismic surveys at The Geysers were disappointing, indicating that the most useful methods were temperature and geochemical surveys (Facca, 1973, p. 2.5).

Stanley, Jackson, and Hearn (1973) had found a closed low-resistivity anomaly associated with the Castle Rock Springs steamfield near The Geysers. The survey showed (Figure 18) a low of about 4 km in diameter and about 10 Ω·m in depth over the steamfield; a low of about 8 km in diameter and about 17 Ω·m in depth over the Clear Lake volcanic field, attributed to chloride-rich pore fluids in the underlying Great Valley Sequence; and a low of about 6 km in diameter and 60 Ω·m in depth over Borax Lake (Isherwood 1981, Fig. 42, p. 89). The resistivity low at Borax Lake (less than 10 Ω·m) was an indication of a possible permeable volume at depth (Kavlakoglu, 1976). This was undoubtedly a factor in selecting Borax Lake for deep geothermal exploration.

E. Geological Associations

Various lithological associations were of interest as possibly having geothermal potential. One association consisted of a permeable reservoir rock overlain by a caprock of impermeable strata (White, 1966). A version consisting of a Franciscan reservoir with a cap of Knoxville Sandstone and Shale, was termed the
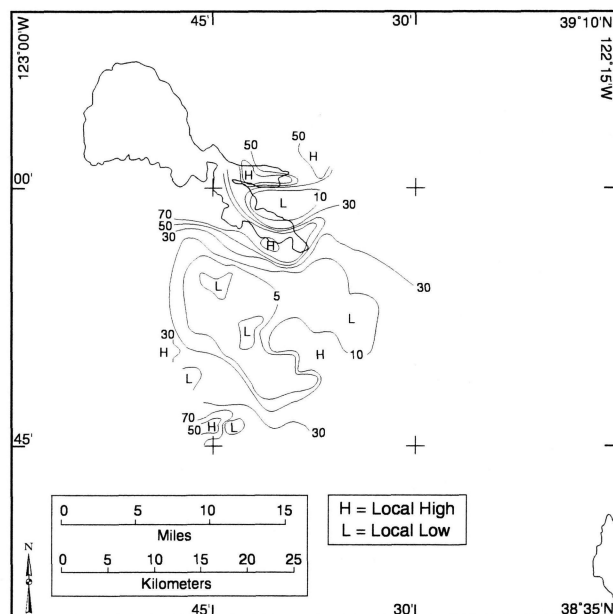
Figure 18: Apparent resistivity contours in the vicinity of Borax Lake. Contours in Ω·m. From Isherwood (1981, Fig. 42, p. 89), after Stanley, Jackson, and Hearn (1973).

"Knoxville model." A well at Wilbur Springs was said to have tested the concept, which failed, and the model was abandoned.

The geological association of interest in the Borax Lake exploration program was a "serpentine structure," that is, massive greywacke associated with a serpentine piercement structure (Facca, 1973). The occurrence of serpentine at Borax Lake was based on old reports. The serpentine body was lost for many years, but it reappears on Manson's map (1989) as a small fault sliver on the roadside in the hills northwest of the lake.

F. Geothermal Gradients

Geothermal gradient wells: The failure of the expensive Bianchi Well No. 1 led to proposals for cheaper exploration methods than wide-spaced deep drilling. A method was proposed (Facca, 1973) for conducting a survey with shallow temperature gradient holes. The argument (Facca, 1973, p. 4.3) was that if there is a widespread steam reservoir at depth, its temperature will be relatively constant everywhere,

independent of the geometry of the cap-rock reservoir boundary. With the assumption that the heat conductivity of the cap rock is constant, the gradient changes with the depth of the permeability barrier between the cap rock and the reservoir. Therefore, such measurements should help to delimit the boundaries of the prospective steamfields. For such a situation at The Geysers, compare Figures 8 and 10 of this report.

Geothermal gradients south of Highlands Arm: The exploration program at Borax Lake began in July 1972. The target was the region between Mt. Konocti and Sulphur Bank Mine, which includes Konocti Bay on the southwest side of Highlands Arm and Borax Lake on the other.

The Wilson, Neasham, and Jorgenson deep wells on the southwest side of Highlands Arm, to depths of 3,353, 2,756, and 3,139 m, respectively, yielded temperature gradients of 92.6, 85.4, and 86.8 mK/m, respectively (Walters and Coombs, 1992, Tab. 3, p. 48).

The Kettenhofen well on the west side of Ely Flat, about 2,414 m (1.5 mi) inland from Konocti Harbor (first named Eureka-Magma in 1971), was taken over and deepened to 2,384 m (7,822 ft) by Getty in 1972, was then taken over and continued to 2,610 m by Pacific Energy Corporation in 1973, and was finally abandoned at 3,828 m. The gradient was about 110 mK/m (Goff and Decker, 1982, Tab. III, p. 19).

A water well at Konocti Harbor Inn was drilled in 1971 to a depth of 137.2 m (450 ft), and another on the Mazzola property, 480 m (0.3 mi) south-southwest, was drilled to a depth of 164.6 m (540 ft). A survey in 1975 found a hot-water aquifer in both wells, extending from a depth of 42.7 to 79.2 m (140 to 260 ft) in the Konocti well. Na-K-Ca geothermometers (Fournier and Truesdell, 1973) were calculated

for some of these wells (Zimmerman, 1975c, Tab. III). The results are tabulated in Table 1.

Geothermal gradient wells at Borax Lake: It was proposed to drill three temperature gradient wells to a depth of 91.4 m (300 ft) around Borax Lake (Facca, 1973). If their gradients exceeded 150 mK/m, then a deep well would be drilled to about 3,048 m (10,000 ft). The locations were first platted on July 14, 1974, and revised on November 8, 1974. Finally, BL-1 (American Petroleum Institute [API] No. 033-90222) was drilled at the western end of the lake on February 6, 1975; BL-2 (API No. 033-90223) on the northern side on February 8, 1975; and BL-3 (API No. 033-90224) on the southeastern shore on February 12, 1975. Temperatures measured at the bottom four days after circulation were BL-1, 33°C; BL-2, 32°C; and BL-3, 41°C (Zimmerman, 1975a).

Temperature logs were run in the wells, with the results shown in Figure 19. The gradients in BL-1, BL-2, and BL-3 were found to be to be 140, 120, and 250 mK/m, respectively (Zimmerman, 1975b, in Lenzer, 1978). Using other data, the writers recalculate the gradients as 135, 104, and 215 mK/m, respectively.
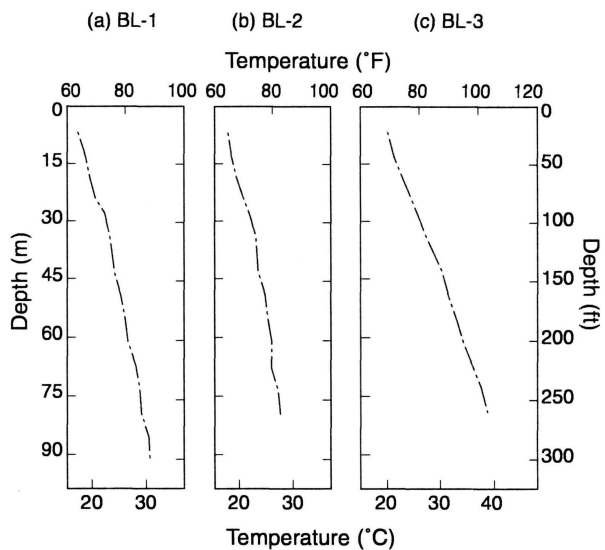
Figure 19: Temperature at depth in shallow wells at Borax Lake. Wells BL-1, BL-2, and BL-3. From Blaydes and Associates (1985, Tab. 2, p. 26, and Fig. 8).

G. The Deep Exploration Well at Borax Lake

Because the geothermal gradient met requirements, the deep well, Borax Lake 7-1, was drilled. The shallow wells had encountered conductive gradients, so the explorers must have supposed they were in a conductive cap overlying a possible steamfield at depth. Microseismic monitoring indicated the presence of an active fault through Borax Lake (Burns, April 1996). The deep well was sited on Franciscan bedrock on the northern flank of the Borax Lake graben, at a site very close to the gradient well BL-2. This well will be described in detail elsewhere. The following is a brief summary.

The Borax Lake 7-1 well (API No. 033-90162) was started on February 16 and completed on April 24, 1978, to a depth of 2,414.3 m (7,921 ft). The lithology was entirely Franciscan sediments and volcanics. Goddard and Goddard (1991), citing J. J. Beall, said a drilling break from 1,446.0 to 1,446.6 m (4,744 to 4,746 ft) produced a gas flow. At 2,414.3 m (7,921 ft) several attempts were made to displace the mud from the hole with water and then unload the hole using drilling rig air compressors. Because of unstable hole conditions, resulting in bridges in the well bore, the deepest blowdown of the well proceeded only to a depth of 1,388.4 m (4,555 ft). While pulling drill pipe out of the well from that depth, the float valve failed and the "well tried to flow." Efforts to stabilize the hole by redrilling it with mud were unsuccessful because the formation caved above the bit. Cement was squeezed into the open hole between 1,193 and 1,844 m (3,914 and 6,050 ft). After drilling out the cement and cleaning the hole to total depth, 73-mm (2-7/8-in.) tubing was run to the bottom for temperature observations.

Temperature logs of the Borax Lake deep well yielded a linear gradient similar to the deep wells southwest of Highlands Arm, as shown in Figure 20. Bottomhole temperatures were 250.3°C (453.6°F) at 2,414 m (7,920 ft) on May 31, 1978, and 238.7°C (461.6°F) at 2,412.5 m (7,915 ft) on August 23, 1978, which is a gradient of 105 mK/m.
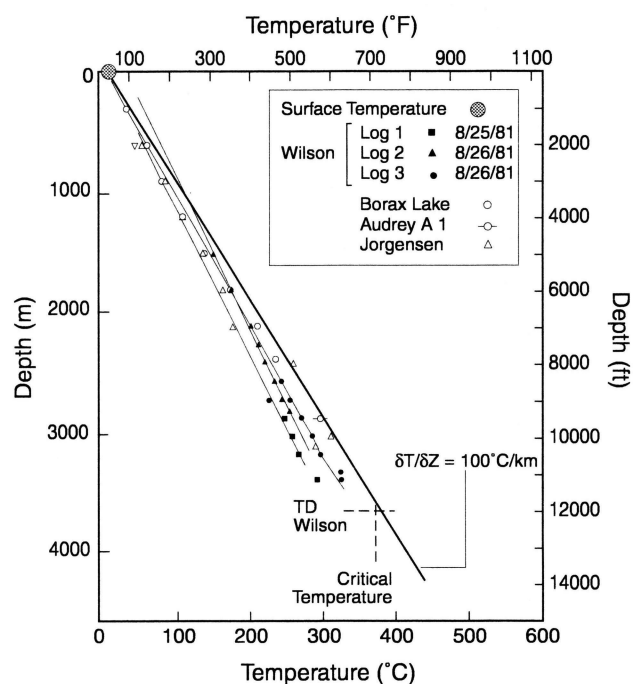
Figure 20: Temperature profile of the Borax Lake deep well, Borax Lake 7-1, showing its similarity to other deep wells south of Highlands Arm. Compiled by R. Potter. Modified from Burns and Potter (1990, Fig. 4, p. 115)

The well was abandoned for lack of productivity. It was proposed to extend exploration to areas farther northeast, using the geochemical exploration stategy. Many years later, a study for Lake County (Goddard and Goddard, 1991) suggested that the well could be used for deep injection as a means of disposing of sewage water. This proposal was preempted by the SE Geysers pipeline.

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VI. HEAT FLOW NEAR THE CITY OF CLEARLAKE

A. Heat Flow Offshore in Clear Lake

From November 2 to 4, 1973, Urban and Diment (1988) measured the heat flow in a diamond drill hole CL-73-7 offshore in Highlands Arm of Clear Lake. The well CL-73-7 yielded a gradient of 149.6 mK/m, corresponding to a heat flow of 100.0 mW/m² (2.39 hfu). Annual solar heating effects were found to penetrate to a depth of 10 m below the lake bottom (Urban and Diment 1988, Fig. 6, p. 214; Martin, 1976, p. 2).

Core drilling is a slow and expensive way to meaure heat flow. Thermistor surveys are less accurate but considerably faster. They have worked well in deep lakes, which in temperate continental climates tend to be stratified, and the temperatures of the deep waters remain fairly constant. Clear Lake, however, tends to be well mixed. In September 1973, Urban and Diment (1988) ran a test of a penetrator in shallow depths in the western part of the lake. The isotherms generally followed the contour of the lake bottom, consistent with a well-mixed water column.

The data obtained from the core drilling extended well below the range of insolation effects, and the heat flows so measured are reliable. Thermistor surveys would reflect the interaction between the steady geothermal gradient and annually varying solar heating of lake waters. The numbers would have no quantitative value without reduction according to an analysis appropriate to that physical situation. However, if the survey is taken rapidly, the effect of the annual process is small and might be removed by taking differences from a control station.

In late April and early May 1975, the State Lands Commission ran a thermistor survey of the lake bottom (Martin, 1976; Martin and Welday, 1977), using a probe designed and built at Lawrence Berkeley Laboratory. Theoretical studies had predicted an annual variation of about 10°C at a depth of 0.8 m. The survey was run in the spring seasonal warmup. The bottom water temperature increased at a rate of 2°C during each week of the survey. In order to remove the warming effect, two control stations were maintained throughout the survey off Indian Beach, and another in the Lakeport basin north of Soda Bay.

Two measurements showed stability. T1 is the temperature at a depth of 0.8 m, corrected to an arbitrary baseline. This is plotted in Figure 21. The value of the data is not the absolute value of T1 at any place, but the difference from place to place. The second measurement is (T1 – T2), the difference in temperature between depths of 0.8 and 0.6 m. This is shown in Figure 22. At some measurement stations, the surveyors observed thermal effects resulting from nearby submarine fumeroles.

The two surveys, T1 and (T1 – T2), were in general agreement in discovering highs at locations A, Oak Cove; B, Point Lakeview; C, between Fraser Point and off Little Borax Lake; and E, off Gooseneck Point. A low was discovered at D, Honeymoon Cove.
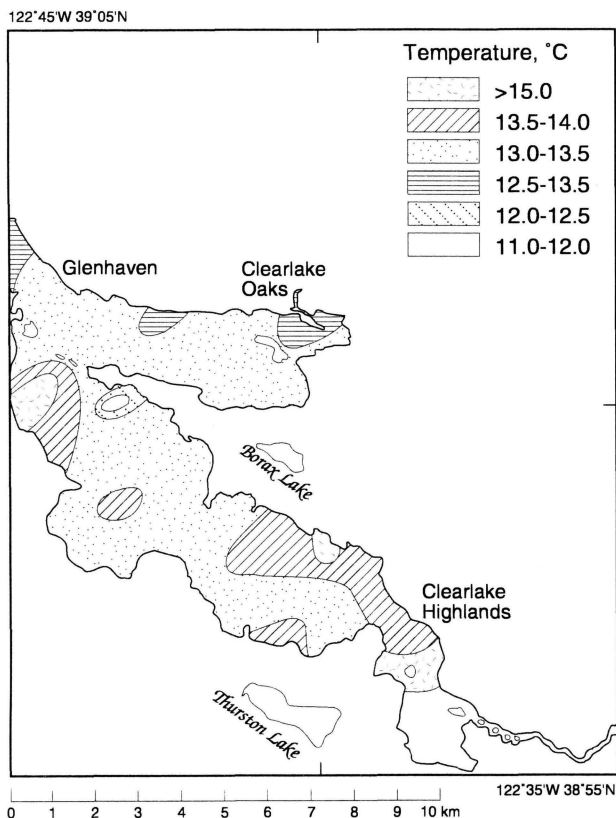
Figure 21: Temperatures (T1) offshore in Clear Lake, April to May 1975, at 0.8 m below the lakebed. After Martin (1976, Fig. 14, p. 9) and Martin and Welday (1977, Fig. 2, p. 202).

The largest anomaly found was at Oak Cove. Figure 23 shows a detailed map of temperature differences. The anomaly is centered about 350 m offshore and is about 0.7 km in diameter. It did not seem to be a submerged hot spring.

An industrial thermistor survey run in 1975, before August, measured the temperature in lake-bottom sediment at 33 locations in the eastern arms of Clear Lake. The results are shown in Figure 24. The contours at 150 mK/m outline a high, elongated N315E along the axis of Highlands Arm reaching maxima of 166 mK/m. Between them on the north side is a rounded low defined by the 130-mK/m contour that is truncated against the north shore in Lily Cove.
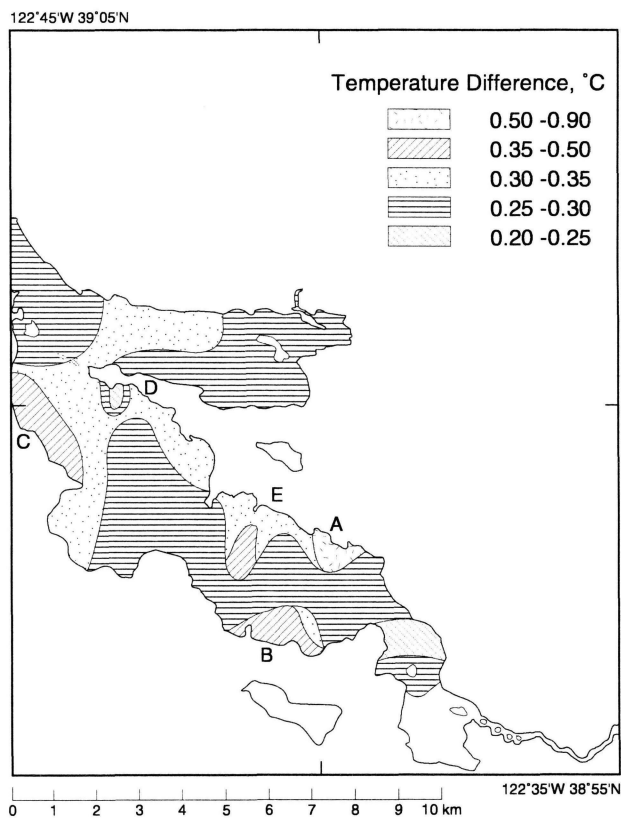
Figure 22: Temperature differences (T1 – T2) offshore in Clear Lake, April to May 1975, between 0.6 and 0.8 m below the lakebed. After Martin (1976, Fig. 15, p. 9).

A high defined by the 130-mK/m contour occupies the central part of Oaks Arm. To the west, a low defined by the 100-mK/m contour comes ashore on the north coast at the point called Indian Beach, about 1.6 km (1 mi) east of Glenhaven. This also is apparently aligned in the direction N315E.

Discussion: The heat flow in the Lakeport basin is only about 63 mW/m² (1.5 hfu). The heat flow in Highlands Arm, at CL-73-7, correcting for a sedimentation rate of 0.68 mm/a, is about 113 mW/m² (2.7 hfu). There is a narrow Cainozoic graben running along the length of Highlands Arm, trending N315E (Sims, Rymer, and Perkins, 1988, Fig. 10, p. 41). The sediments in the graben
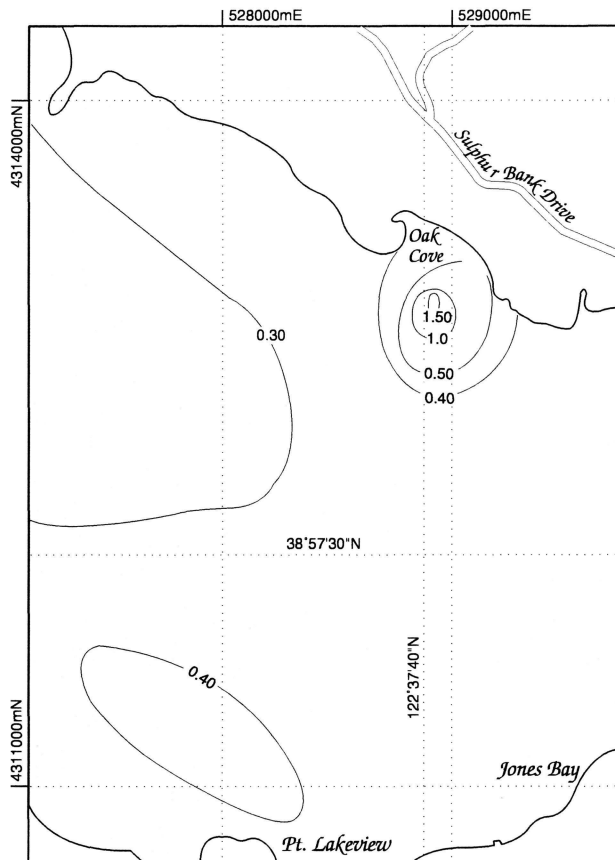
Figure 23: Temperature differences (T1 – T2) offshore at Oak Cove, April 1975, between 0.6 and 0.8 m below the lakebed. After Martin (1976, Fig. 19, p. 12), and Martin and Welday (1977, Fig. 3, p. 203). From Burns and Potter (1993, Fig. 8, p. 320).

Figure 24: Temperature gradients offshore in Clear Lake. Contour interval 10 mK/m. From Zimmerman (1975c, Fig. 18).

could be as much as 1.2 km thick. The thermal conductivity of the sediments in the graben is a small fraction of that of the rocks underneath and on the flanks. Models of the effect of refraction of heat flow in this geometry were developed by Von Herzen and Uyeda (1963). Using the models, Urban and Diment (1988, Fig. 8, p. 219) show that the heat flow at depth under Highlands Arm could be as much as three times the value observed at the surface. The geothermal gradient should rise steeply in the center of the lake because of the blanketing effect of the sediments. The results in Figure 24 are in accord with these expectations.

B. Heat Flow Onshore Near the City of Clearlake

Geothermal gradients for the Borax Lake area are shown in Figure 25. This is left in the original units because recomputation and recontouring would distort the image. The diagram indicates three highs, with values of 466.7, 120.3, and 315.4 mK/m (25.6, 6.6, and 17.3°F/100 ft), located over the Sulphur Bank Mine, Borax Lake, and Burns Valley, respectively.
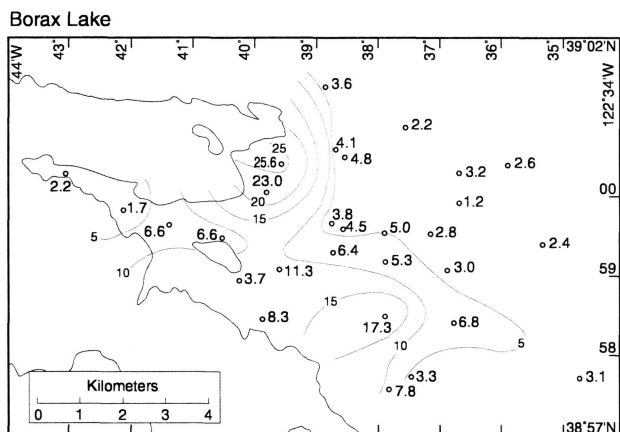
Borax Lake

Figure 25: Temperature gradients in the vicinity of Borax Lake. Contours are 5, 10, 15, 20, and 25°F/100 ft, corresponding to 91, 182, 273, 365, and 456 mK/m. From Johnson (1992, Fig. 8, p. 13).

A second interpretation of the heat flow, based upon more and different data, is shown in Figure 26. The figures confirm the existence of two highs, one over Sulpher Bank Mine and another over Burns Valley. The heat flow around the Sulphur Bank Mine spring has the form of a spike. The spike is concave upwards in cross section, as illustrated in Figure 27.

There is insufficient information in Figures 25 and 26 to clarify the situation at Burns Valley, but it seems very likely that with sufficient data, it would take the shape of a spike, in the same way as at the Sulphur Bank Mine. The Burns Valley anomaly was not located using geothermal gradient wells, and after a great deal of additional work, it was finally defined by geochemical tracers, as will be shown subsequently.
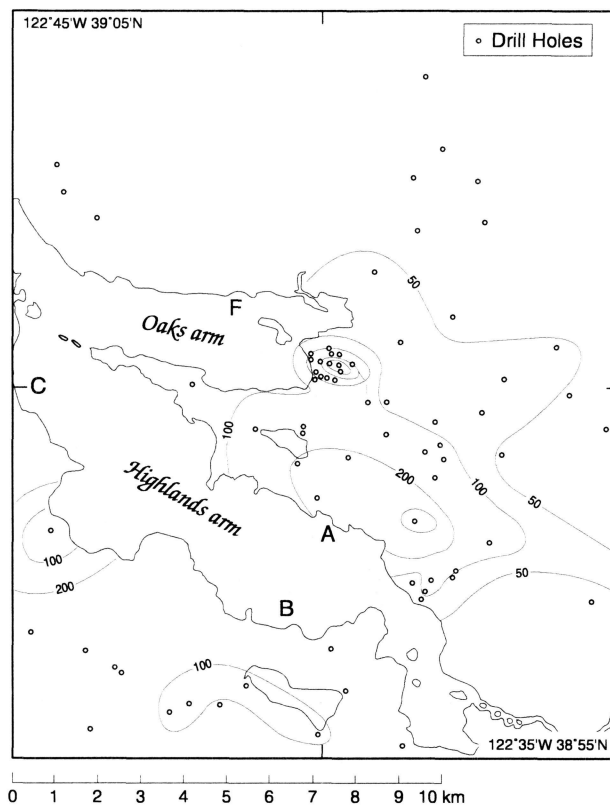
Figure 26: Geothermal gradients in the vicinity of Clearlake. Based on shallow gradient wells. Contours are labeled in units of mK/m. From Burns and Potter (1993, Fig. 4, p. 319).
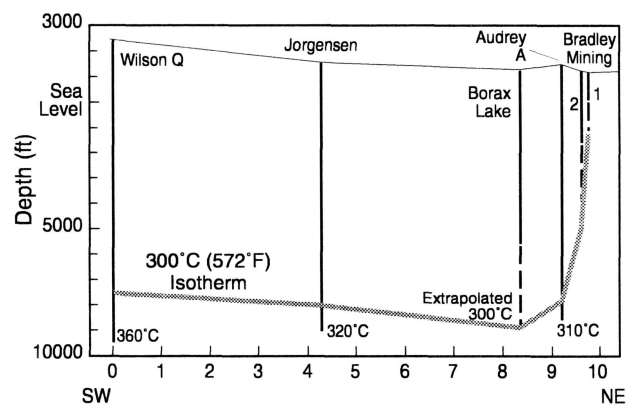
Figure 27: Cross section of the Borax Lake area, showing the 300°C isotherm at depth. Compiled by R. Potter. From Burns, Potter, and Zyvoloski (1992, Fig. 4, p. 138).

VII. HOT-WATER RESOURCES OF BURNS VALLEY

A. Introduction

In about 1984, the City of Clearlake instituted a program of investigation of the city's geothermal resources with the support of the California Energy Commission. Geothermal policy for the City of Clearlake has been coordinated at different times by Donald M. Bayer, Richard Spitler, and Daniel A. Obermeyer.

B. Phase I Study

A Phase I study was completed in May 1985 (Figure 28). This identified community characteristics, potential direct-use applications, and city planning and development measures. The report also reviewed the pertinent geologic literature, industry data from nearby drill holes that had entered the public domain, and water chemistry data.

The study used data from three exploration wells at Borax Lake, two surface water samples, one hot spring, and 15 domestic and irrigation water wells distributed throughout the city. Summary analyses for these waters are listed in Table 2, and locations are shown on Figure 28; a nineteenth analysis is omitted because of questions of provenance. The study recommended five areas within the city limits for detailed geothermal evaluation, based on considerations of heat flow and the intersection of faults extrapolated from the sides into the valley (Stone, 1986), as shown on Figure 28.

C. Phase II Study

Introduction: A Phase II study, also supported by the California Energy Commission, was completed in June 1987. A locality map of the survey region is given in Figure 29. The survey region is the principal urbanized area of the city, which caused difficulties in the geophysical surveys.

Geology: The geology of part of the City of Clearlake is shown in Figure 30. Cainozoic volcanics of the Clear Lake Volcanic Formation occur as scattered small outcrops, with a large area of Quaternary rhyolite lying northwest of the city along Arrowhead Road, so named because of an Indian quarry in the rhyolite. This is the youngest rhyolite in the Clear Lake volcanic field, with an age of 0.091 ± 0.013 Ma (between 78,000 and 104,000 years old), according to Donnelly-Nolan, Hearn, Curtis, and Drake (1981). The Eastlake Graben extends northwest off the map, where it joins a larger structure, the Borax Lake Graben. The Eastlake Graben is aligned with the Peachtree Crossing Fault, a large Cainozoic strike-slip fault with San Andreas affinities, trending N305E. The form of the interaction between the Burns Valley and Peachtree Crossing Faults is not known.

The fault trending N060E is the Burns Valley Fault, a deepseated structure transverse to the regional trend of the Coast Ranges. The fault has a very large downthrow to the southeast. Northwest of the fault, the predominant bedrock is Jurassic-Cretaceous Franciscan volcanics. Quaternary alluvium occupies the valley floor. To the southeast, the predominant bedrock is younger Cretaceous sediments.

No.	Well Name	Loc. (s,b)	Date (m,d,y)	Ref.	Temp. (°C)	pH	Li mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	F mg/L	Cl mg/L	B mg/L	HCO$_3$ mg/L	SiO$_2$ mg/L	SO$_4$ mg/L	TDS mg/L	Na-K-Ca (β)	(°C)	Qch (°C)	Qst (°C)
1	Holm's well	18K	8/09/76	1	40	6.2	0.50	110	14.8	175	130	0.21	74	152	1440	124	8	2235	4/3	66	124	143
2	Reid's well	16P	8/04/76	1	25	5.9	0.13	117	6.6	163	61	0.32	136	115	884	93	4	1600	4/3	45	106	129
3	CL surface	28D	-/---/---	1	24	5.7	0.02	22	3.0	24	16	0.15	30	1.55	232	6	1	336	4/3	43	OOR	33
4	Cold well	34F	8/--/76	2	20	5.9	----	----	---	---	--	---	40	---	---	---	---	---	---	---	---	---
5	BL spring	07R	2/19/75	1	15	5.3	BDL	5.1	2.4	5	6.3	BDL	3.1	BDL	86	24	1	135	4/3	52	39	75
6	BL surface	07R	2/19/75	1	--	9.3	0.77	1900	195	7	49	0.39	3510	156	4430	18	36	10302	1/3	OOR	27	65
7	Domestic	21L	6/30/77	3	26	5.6	----	35	2.5	20	38	---	31	1.3	[290]	---	2	320	4/3	45	---	---
8	Domestic	22B	9/16/68	3	18	6.9	----	26	---	39	26	---	19	---	[232]	---	--	----	---	---	---	---
9	Domestic	15J	6/30/77	3	28	6.9	----	22	2.1	35	21	---	11	0.5	[252]	---	5	236	4/3	28	---	---
10	Domestic	15N	8/31/73	3	20	6.7	----	28	0.6	14	8.5	---	9.4	0.8	[134]	---	2.8	190	4/3	15	---	---
11	Domestic	21H	9/19/60	3	20	6.9	----	19	0.9	26	24	---	10	0.5	[198]	---	0.0	208	4/3	12	---	---
12	Domestic	27C	6/30/77	3	24	7.3	----	19	1.3	28	18	---	7	0.0	[208]	---	5	197	4/3	19	---	---
13	Domestic	22B	6/10/75	3	18	6.8	----	53	0.0	51	33	---	25	0.3	[237]	---	90	501	---	---	---	---
14	Domestic	21J	8/11/67	3	--	---	----	28	---	60	34	---	13	1.2	[400]	---	---	---	---	---	---	---
15	Domestic	21J	9/12/72	3	17	7.2	----	33	2.1	57	34	---	15	1.2	[404]	---	1.2	418	4/3	23	---	---
16	Domestic	21L	6/08/71	3	22	5.6	----	32	2.3	84	37	---	28	0.7	[482]	---	0.5	459	4/3	19	---	---
17	BV School	21L	3/25/85	4	19	6.2	----	30	1.8	83	38	---	18	0.45	550	67	BDL	520	4/3	13	87	115
18	Bartram's	21H	3/25/85	4	19	7.3	----	15	0.6	23	15	---	10	0.22	170	43	8.9	230	4/3	3	64	97

Table 2: Analyses of natural and well waters in the City of Clearlake. All measures are metric. BL = Borax Lake. CL = Clear Lake. BV = Burns Valley. TDS = total dissoved solids. BDL = below detectable limit. The parentheses indicate HCO$_3$ calculated from (HCO$_3$) = (CaCO$_3$)/0.8203. Sampling dates (m,d,y) are month, day, year. Locations (s,b) are 640-acre sections and 40-acre blocks in T13N, R7W, MD B&M. Compiled in September 1984, May 1985, and June 1987. After Blaydes and Associates (1985, Tab. 2, p. 26) and Stone (1987, Tab. 8, p. 70). Geothermometers calculated after Fournier (1977). OOR = out of range.

References are

(1) Thompson, Goff, and Donnelly (1978), a USGS Open-File Report, later published as Thompson, Goff, and Donnelly-Nolan (1981). Their sample numbers were Holm's warm domestic well, CLW-85; Reid's well, CLW-82; a spring on the northeast shore of Borax Lake, LJ-75-4; Clear Lake surface waters at Clearlake Highlands from the boat ramp near the sewer outfall, LC-76-12; and the surface waters of Borax Lake, LJ-75-5.

(2) a personal communication from Fraser Goff (1993). The cold well, CLF-27, was at B&B Lighthouse Resort.

(3) unpublished data of the California Department of Water Resources.

(4) data collected in 1985 from Burns Valley School irrigation well and Bartram's irrigation well (Blaydes and Associates, 1985).
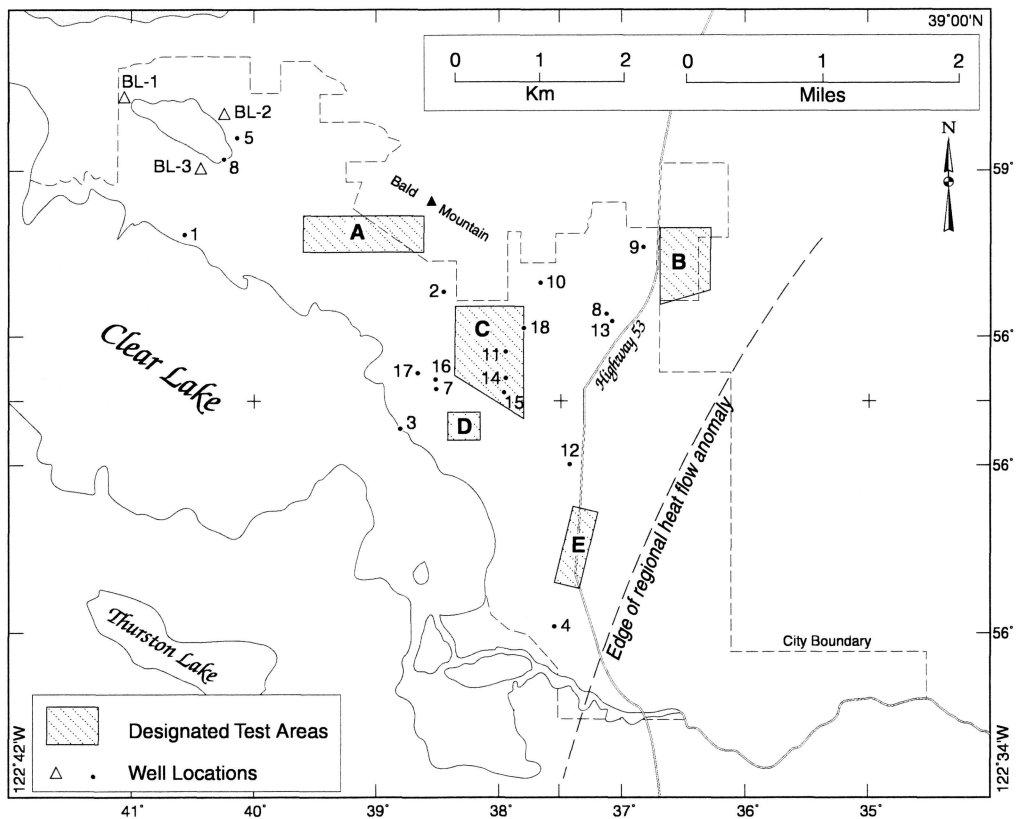
Figure 28: Geothermal investigation of the City of Clearlake, Phase I, 1985. The study used data from the geothermal gradient wells BL-1, BL-2, and BL-3; and water sampled from surface waters, springs, irrigation wells, and domestic wells, as listed in Table 2. The shaded areas A to E were selected for further investigation. From Blaydes and Associates (1985, Fig. 6, p. 83; Fig. 9, p. 86) and the records of the California Division of Oil and Gas.
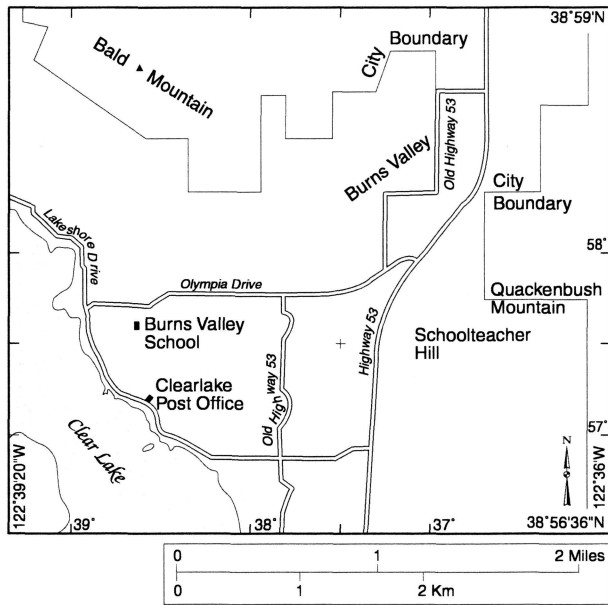
Figure 29: Locality map of Burns Valley. Based on U.S. Geological Survey map sheet "Clearlake Highlands," 7.5-min series, scale 1:24,000, 1958 and 1975.
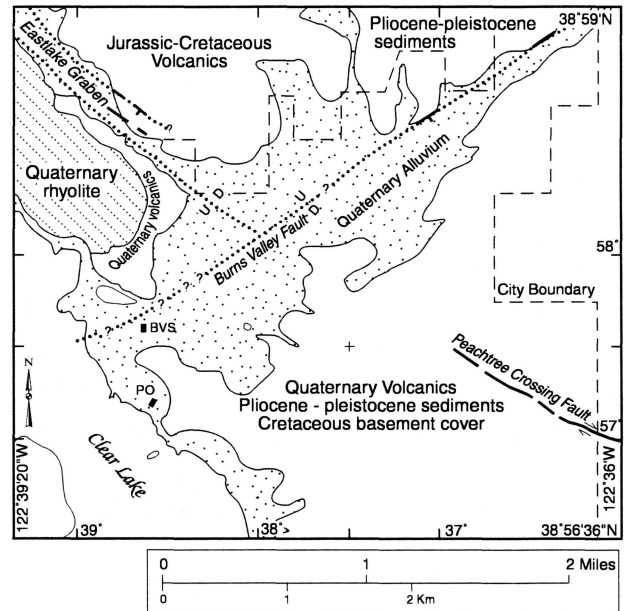
Figure 30: Geology of Burns Valley. From Manson (1989, Map 16), based in part on Hearn, Donnelly-Nolan, and Goff (1975) and Stone (1987, Fig. 3 p. 46).

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Geothermometry: A number of domestic wells in the City of Clearlake were tested for groundwater quality by the Department of Water Resources. Locations of these wells are included in Figure 31.
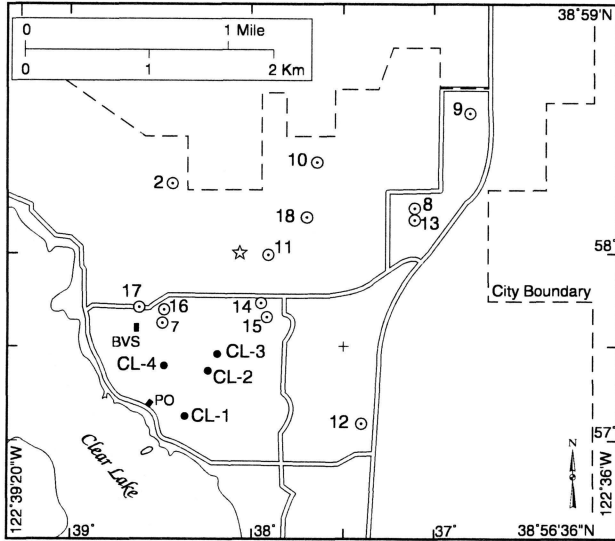
Figure 31: Well locations in Burns Valley. Wells Nos. 2 to 18 are domestic and irrigation water wells as in Table 2. After Stone (1987, Fig. 14, p. 57). Wells Nos. CL-1 to CL-4 are geothermal gradient holes drilled following the thermistor and radon surveys, after Stone (1987, Fig. 8, p. 51). The star marks the site of a proposed geothermal exploratory well, at the Community Center, after Obermeyer (1991).

The Clearlake groundwaters contain, in order of decreasing concentrations, HCO_3, Ca, Mg, Na, Cl, SO_4, and K. The surface and underground waters are chemically similar. The measured temperature of ground waters ranges from 15°C to 40°C, averaging 22.1°C (Table 2).

The analyzed silica versus measured temperature indicated the solubility of chalcedony, as compared to amorphous silica in the Clear Lake volcanic field (Goff, Donnelly, Thompson, and Hearn, 1977, Fig. 2, p. 512). Calculated geothermometers from underground waters are given in Table 2. The mean values of the Na-K-Ca, chalcedony, and quartz

geothermometers, respectively, are 28.4°C, 84.1°C, and 112.8°C.

The silica concentrations are high. This could be due to acid reactions. Seeps of H_2S and CO_2 occur in the area. From consideration of the silica content as a function of temperature, it was thought that some of these waters may have equilibrated with chalcedony, so that chalcedony would appear to be the appropriate silica geothermometer to use for Clearlake waters (Stone, 1987).

The geothermometry results suggested that there might be a low-temperature resource beneath the city with the temperature range 70°C to 75°C (Stone, 1987). The areas "A" and "B" of Figure 32 were selected for geophysical surveys, comprising thermistor, radon, and electromagnetic surveys.
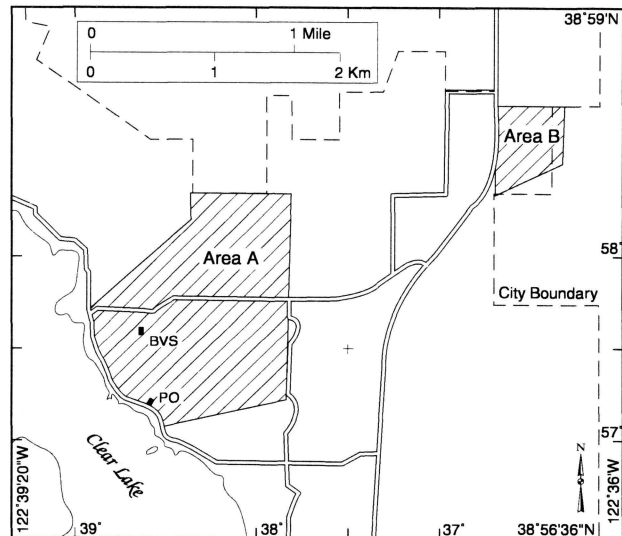
Figure 32: Areas of Burns Valley selected for geophysical surveys. Areas "A" and "B" were delineated. After Stone (1987, Fig. 2, p. 45).

Thermistor survey: The temperature surveys were conducted by setting temperature probes in holes drilled 3 m deep using a truck-mounted auger rig. Eighty holes were drilled altogether, 61 in area "A" and 19 in area "B," spaced about 182.9 m (600 ft) apart. A refer-

ence probe showed that drift was negligible and did not exceed the 0.5°C accuracy of the tool, so no drift correction was applied. The correction for elevation was 0.01°C for every meter increase in elevation above a reference datum, which was at an altitude of 408.4 m (1,340 ft above sea level [asl]) for area "A" and 426.7 m (1,400 ft asl) for area "B." A correction of +1°C was made for holes located in areas of very dense vegetation (Stone, 1986). The results are shown in Figures 33 and 34.

The mean of all 61 temperature measurements in area "A" is 17.62 ± 2.1°C. The area to the north contains a hot well, but the survey found no anomalous temperatures. That might be due

to groundwater recharge from Bald Mountain or irrigation of the walnut orchards. Anomalously high temperatures were discovered in the southwest part of area "A," near the post office, as shown in Figure 33. The anomaly is bounded by a 20°C contour, open to the south. A well-defined high extends from Ridge Avenue down toward Redbud Park.

The mean of 19 measurements in area "B" is 17.3 ± 0.8°C. The temperatures varied by less than 3°C and exceeded the mean annual air temperature by little more than 3°C. Accordingly, if a shallow temperature anomaly exists beneath area "B," it is not hot enough to be detected by this method.
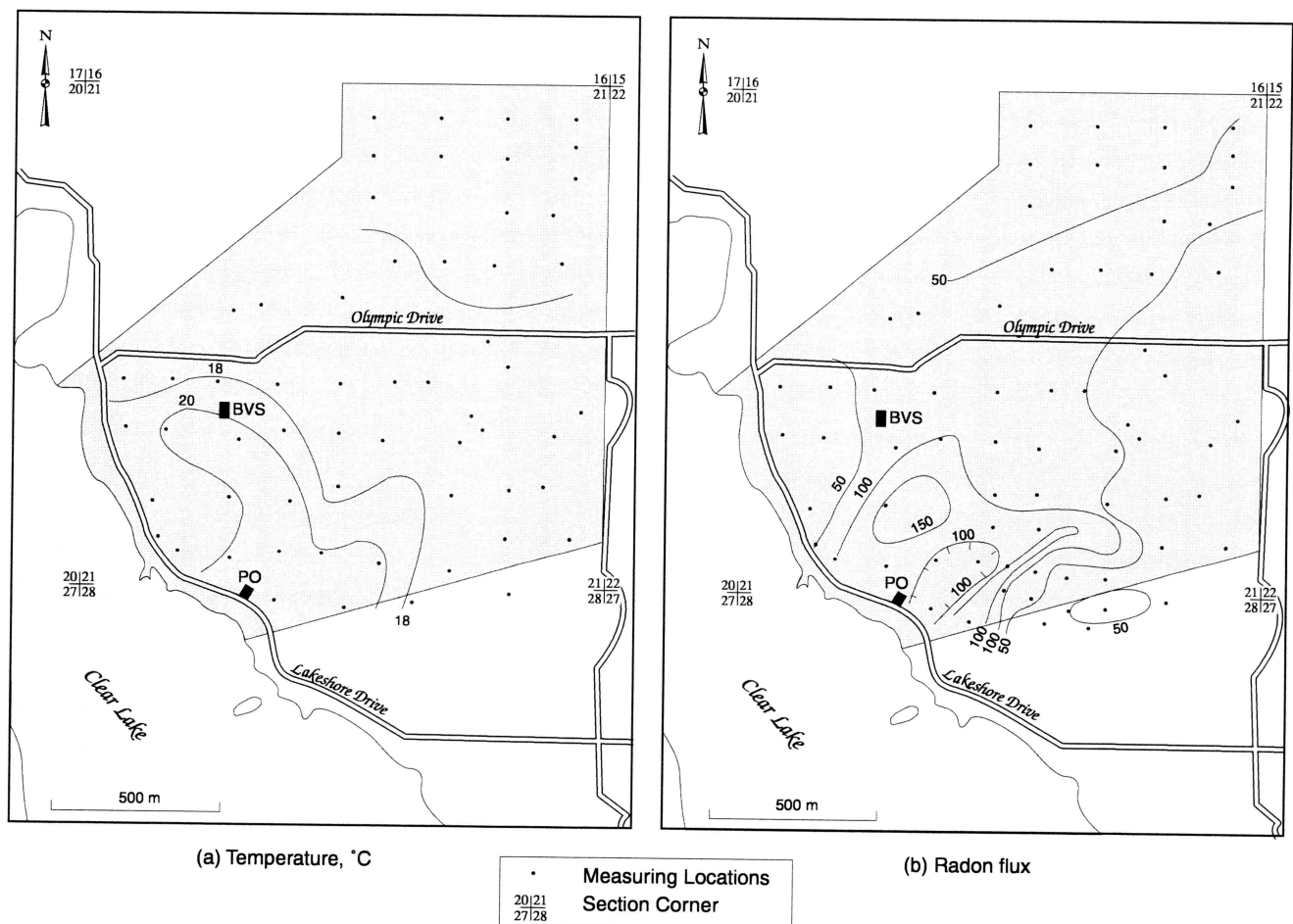
Figure 33: Maps of temperature and radon flux for Area "A." (a) Temperature in °C. (b) Radon flux (for units see explanation in text). The solid dots represent measuring locations. BVS = Burns Valley School, PO = Clearlake Post Office. After Stone (1987, Fig. 4, p. 47 and Fig. 6, p. 49).
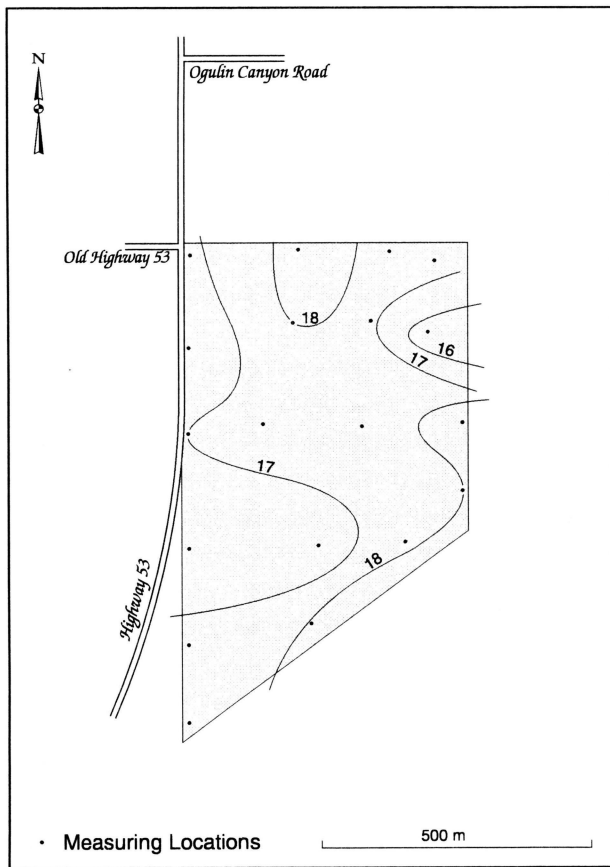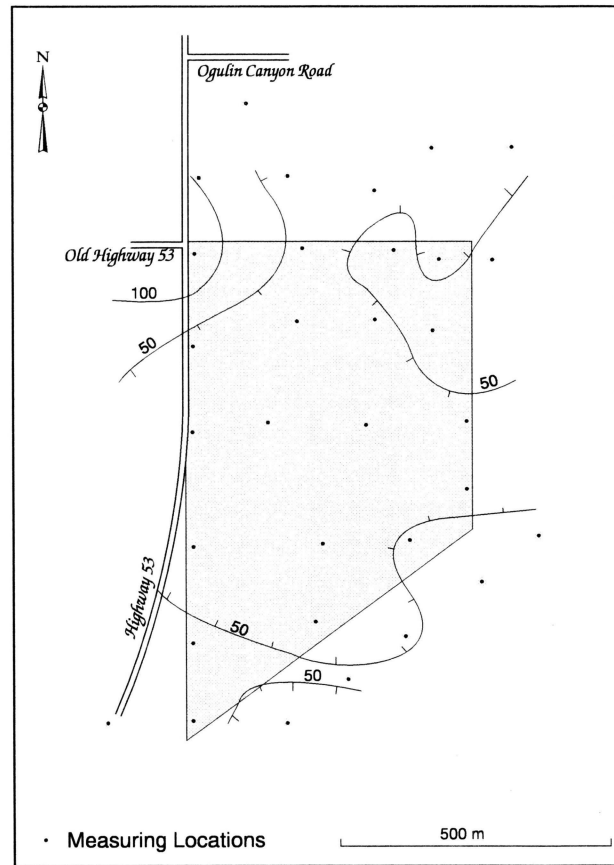
(a) Temperature, °C   (b) Radon flux

Figure 34: Maps of temperature and radon flux for Area "B." (a) Temperature in °C. (b) Radon flux (for units see explanation in text). The solid dots represent measuring locations. After Stone (1987, Fig. 5, p. 48 and Fig. 7, p. 50).

Radon surveys: Surveys for radon gas in the soil were made using the Terradex Track Etch system. Radon detectors were buried at a depth of 0.38 m (15 inches) for about 30 days. They were then recovered and sent to the manufacturer who counted the number of tracks (t) per square millimeter of detector, and normalized the results to a 30-day datum. The resulting value (t/mm^2) was termed the radon flux.

A soil sample was collected from the bottom of the holes at the time the detectors were buried. The sample was analyzed separately for radon in the soil, and that value was subtracted from the radon flux. The final value is the soil-reduced radon flux.

Seventy-four detectors were buried in area "A," and 34 in area "B." Stations were spaced

at intervals of 182.9 m (600 ft) where possible. In the vicinity of a possible fault intersection in area "A," the spacing was decreased to 91.4 m (300 ft). Additional detectors were placed around the periphery of area "B" to increase the coverage.

The radon survey in area "A" found an anomalously high area, exceeding 150 t/mm^2, in the southwestern part of area "A," between the Burns Valley School and the post office, under Ridge Road and Cresta Avenue (Figure 33b). This coincided with the thermal anomaly.

The radon survey in area "B" found nothing of significance, except perhaps in the extreme northwest corner, at the junction of Old Highway 53 with the new Highway 53 (Figure 34b).

Electromagnetic surveys: Transient electromagnetic (TEM) soundings were conducted in Burns Valley before November 1986. The object of the TEM survey was to map the subsurface rock resistivity in an attempt to determine the location and extent of hot-water zones. The central, or in-loop configuration was used to provide a relatively focused sounding to depths of several hundred meters. The method excites a toroidal waveform that travels vertically downward and generates a secondary field according to the resistivity at that depth, which is detected by the central receiver.

The transmitter was a square loop of dimensions ranging from 61.0 to 304.8 m (200 to 1,000 ft) on a side, laid out on the ground. The receiver was a coil loop placed at the center of the transmitter. The transmitted (primary) waveform was a standard square wave with a 50% duty cycle; the measurements on the secondary field were made during the off times between the positive and negative transmissions. The decay curve was sampled at 30 points from 0.089 to 72 ms. A total of 28 stations were occupied, denoted A1 to A15 and B1 to B14, at locations shown by the squares in Figure 35. The survey design called for transmitter sizes of 92.9 m² (1,000 ft²); however, power lines and other cultural noise restricted the size to 46.5 m² (500 ft²) or less. Most stations did not yield measurable data in all 30 channels because of local noise and limitations on the maximum size of the transmitter loop.

Raw data decay curves: The TEM data from the 28 field stations were processed to yield apparent resistivities as a function of decay time. The raw data decay curves (Table 3) in Area "A" exhibit a conductive surface layer and a second conductive layer at depth. In Area "B" (Table 4), a deep conductive zone occurs at stations B1, B7, and B12 in the south-central part of the area. To the north, the data from stations B5, B8, and B14 also exhibit a double conductive layer, with B14 somewhat uncertain because of noise.
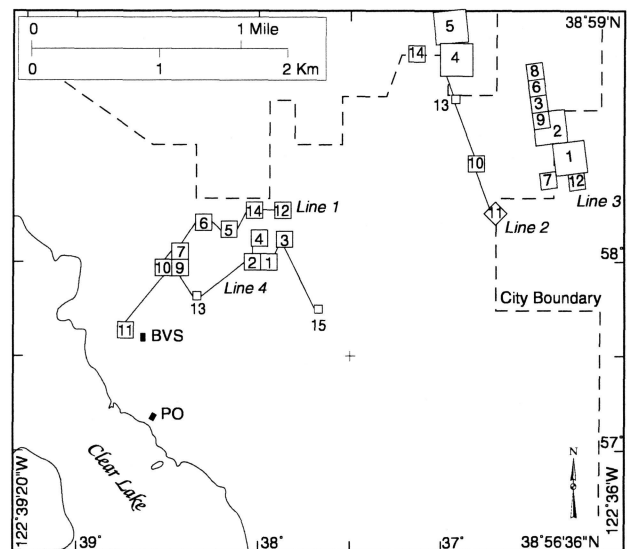
Figure 35: TEM survey stations and profile lines 1 to 4, Burns Valley. After Electromagnetic Surveys, Inc. (1986, p. 3).

Maps of apparent resistivity: The results are presented as maps of apparent resistivity in Figures 36 and 37, at time slices 0.22, 0.72, 2.2, 7.2, 22, and 72 ms. The maps do not show dramatic lateral variations. They show poorly defined resistivity lows, which seem to reflect basement topography at 2.2 ms and bedrock structure at 7.2 and 22 ms. The apparent resistivities are quite low, relative to other areas in the district. There is not enough detail to establish correlations with faults. Within Area "A," stations A11 and A15 show the most conductive response. Both lie near inferred faults (Figures 36c and 37a). The maps of Area "B" suggested that there may be a conductor near station B13 (Figures 36b, 36c, and 37a).

A1	A2	A3	A4	A5	A6	A9a	A10	A11	A12	A13	A14	A15
Depths of tops of lithological units in meters												
0	0	0	0	0	0	0	0	0	0	0	0	0
11	49	14	30	39	33	48	50	27	35	42	26	49
21	98	100	79	87	70	99	100	74	78	108	69	101
157	147	124	141	141	80	147	150	133	113	214	208	159
383	196	---	156	---	92	154	170	188	177	---	---	259
---	245	---	429	---	298	273	269	220	194	---	---	339
---	---	---	492	---	---	---	---	---	---	---	---	388
Resistivity of lithological units in Ω·m												
172	14	18	19	16	23	22	29	10	18	42	18	83
6	9	10	7	6	6	6	6	5	8	66	9	6250
12	23	529	38	399	14	34	112	13	338	106	1276	935
71	13	7258	79	3245	2	5	4	28	274	89	1293	50
1290	74	---	59053	---	365	270	1857	3	176	---	---	34
---	900	---	428	---	442	93668	653	164	886	---	---	6
---	---	---	1322	---	---	---	---	- - -	---	---	---	1407

Table 3. Raw data decay curves for TEM survey of Area "A." Field observation stations were numbered A1 to A15. The top part of the table lists the depths to the top of the several lithological units at each station. The bottom part of the table lists the corresponding resistivities, in Ω·m. After Electromagnetic Surveys, Inc. (1986, App. II).

B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
Depths of tops of lithological units in meters													
0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	51	50	49	50	56	18	29	41	47	26	10	43	40
193	116	100	99	158	105	108	68	97	101	69	93	86	136
251	157	150	149	744	160	144	111	152	148	98	336	160	188
273	194	200	212	772	204	185	170	187	188	144	506	---	---
286	239	250	---	919	248	336	234	247	266	198	642	---	---
489	293	300	---	---	---	496	297	280	---	275	---	---	---
499	363	350	---	---	---	553	367	---	---	351	---	---	---
Resistivity of lithological units in Ω·m													
29	37	20	16	37	33	24	34	23	16	37	33	19	25
19	15	16	8	17	19	20	14	16	24	8447	37	6	12
30	41	135	60	288	47	680	32	65	116	49	21	6	17
9	21	46	68	2	51	61	15	21	16	14	15	1139	55106
8	15	9	69793	18	28	16	21	10	12	210	4	---	---
61	14	22	---	0.7	22	17	44	19	26	12	1	---	---
8	17	35	---	---	442	139	3	32	---	45	---	---	---
5	21	21	---	---	---	4	4	---	---	21	---	---	---

Table 4. Raw data decay curves for TEM survey of Area "B." Field observation stations were numbered B1 to B14. The top part of the table lists the depths to the top of the several lithological units at each station. The bottom part of the table lists the corresponding resistivities, in Ω·m. After Electromagnetic Surveys, Inc. (1986, App. II).
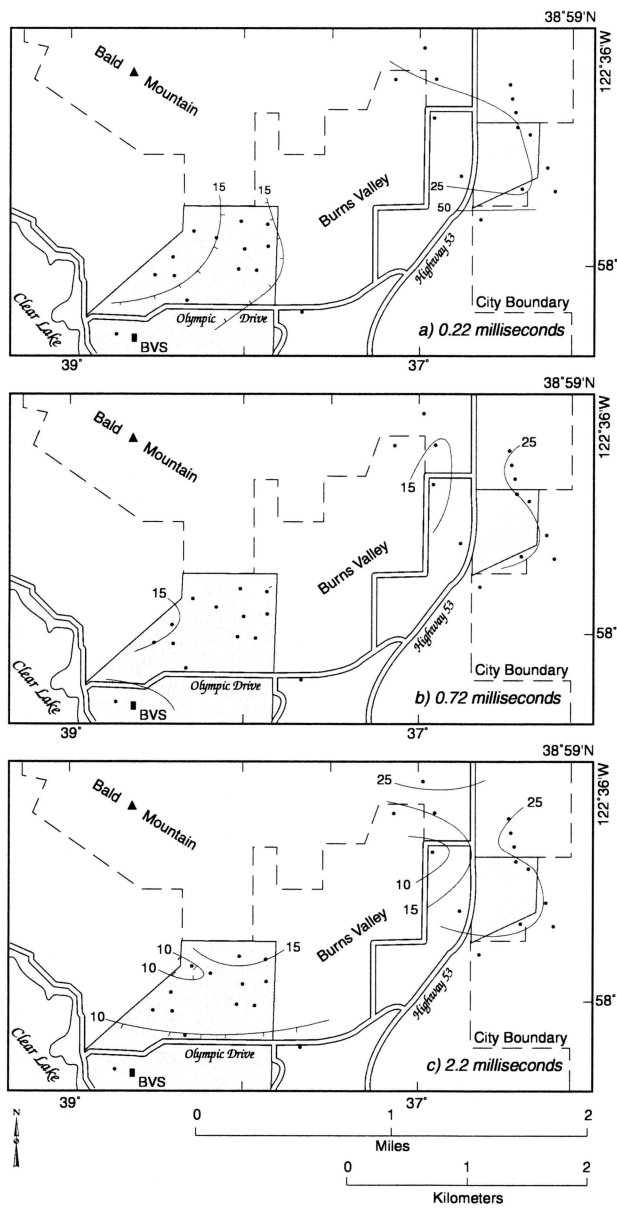
Figure 36: Maps of apparent resistivity at time delays of 0.22, 0.72, and 2.2 ms—(a) 0.22 ms; (b) 0.72 ms; (c) 2.2 ms. After Electromagnetic Surveys, Inc. (1986, pp. 17–20).
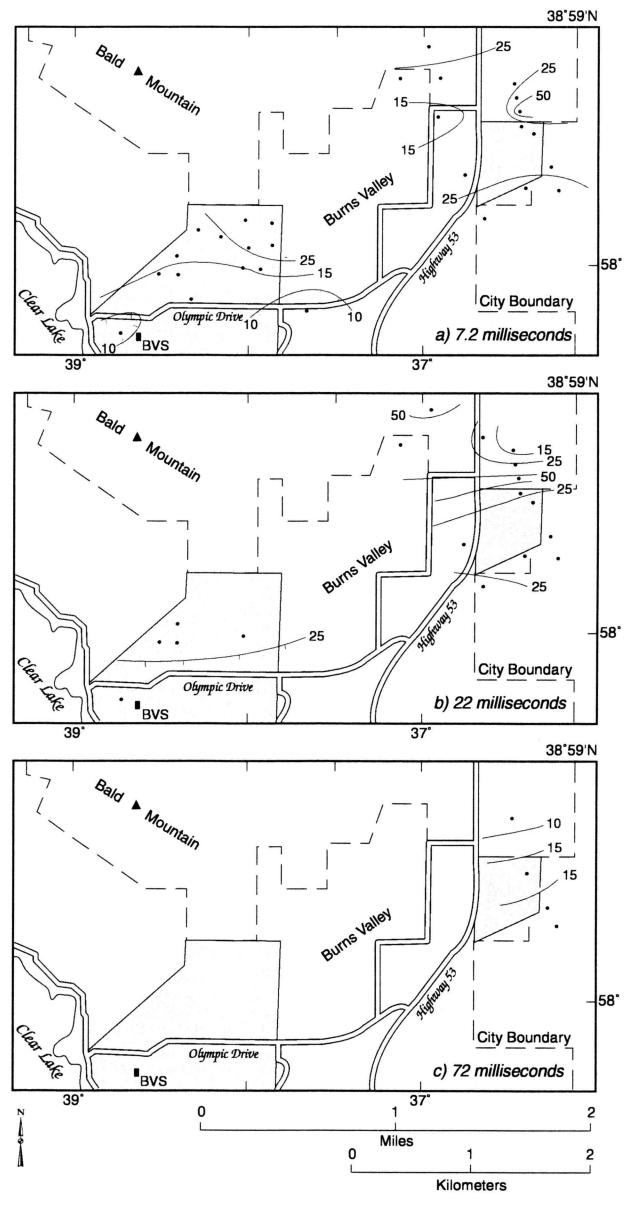
Figure 37: Maps of apparent resistivity at time delays of 7.2, 22, and 72 ms—(a) 7.2 ms; (b) 22 ms; (c) 72 ms. After Electromagnetic Surveys, Inc. (1986, pp. 17–20).

Pseudosections: The results are presented as pseudosections in Figures 38 and 39. For Area "A," line 1 showed a resistivity low (<10 Ω·m) open to the southwest at station A11—this must connect to the waters of Clear Lake. Line 1 intersected a tubular low (<10 Ω·m) which runs under stations A5 and A6 and could represent the bedrock surface over the fault on the NE side of the Borax Lake graben (Figure 38a). A large conductor extends over the whole of line 4, with a maximum depth at station A15 (Figure 38b).

For Area "B," line 2 showed a tubular low under station B13 that could represent a bedrock depression over the Burns Valley Fault (Figure 39a). The most interesting anomaly was line 3 (Figure 39b), which shows a very strong edge effect at the north end of the line at station 8 as a result of the Burns Valley Fault, which appears to pass under the station at depth. Another conductive target was apparent at depth in line 3 at the south end of the line, at stations B1 and B12 (Figure 39b).
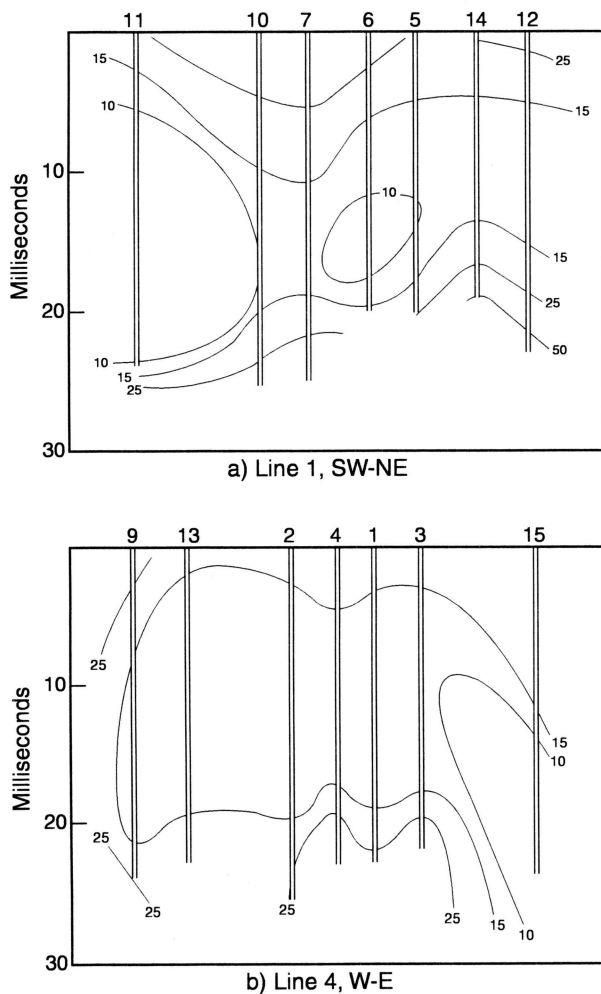
Figure 38: Pseudosections of apparent resistivity in Area "A." Isolines 10, 15, 25, and 50 Ω·m. The spread stations 11, 10, 7, 6, 5, 14, and 12 are shown in Figure 35. The traverse lines are (a) line 1, SW-NE; (b) line 4, W-E. After Electromagnetic Surveys, Inc. (1986, pp. 24, 26).
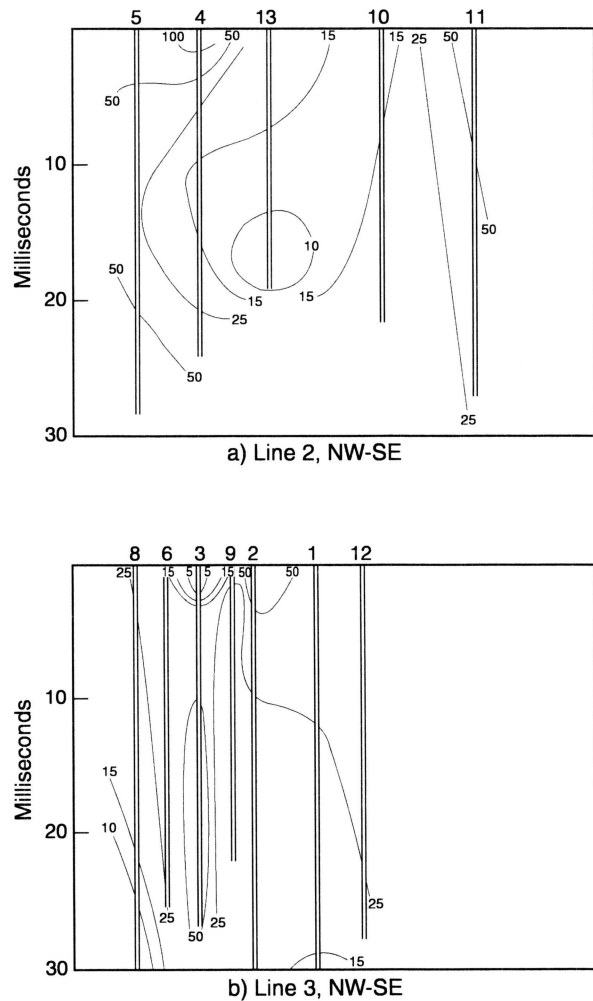
Figure 39: Pseudosections of apparent resistivity in Area "B." Contours 10, 15, 25, and 50 Ω·m. The spread stations 5, 4, 13, 10, and 11 are shown in Figure 35. The traverse lines are (a) line 2, NW-SE; (b) line 3, NW-SE. After Electromagnetic Surveys, Inc. (1986, pp. 24, 25).

Inversion model sections: The decay curves from the 28 stations were inverted by using a multilayer inversion algorithm. The results are presented in Figures 40 and 41. In Area "A," line 1, a conductive zone is present that becomes deeper toward the southwest, that is, toward the lake. The highest conductivity and largest conductive zone is at station A11 (Figure 40a). On line 4, a small conductor is located at station A9. The thickest surface conductive zone is at stations A1 and A2. A conductor may occur at a depth of 366 m (1,200 ft) at station A15 (Figure 40b).

For Area "B," a deep conductor occurs at the northern end of line 2, at station B5. A shallow conductor appears at station B13 (Figure 41a). On line 3, the largest conductive zone in Area "B" occurs on line 3, at depth at the south end, in stations B1 and B12. The inferred depth to resistive basement on line 3 is about 290 m (953 ft) northwest of the fault, and 632 m (2,073 ft) southwest of the fault, implying a throw on the Burns Valley Fault of 342 m (1,120 ft). A conductor also appears at station B8, which may connect with that at station B5 (Figure 41b).

Figure 40: Interpreted resistivity in Area "A." Ranges of apparent resistivity are <=5, 5–15, 15–25, and >25 Ω·m. The lines are shown in Figure 35: (a) line 1, SW-NE, (b) line 4, W-E. After Electromagnetic Surveys, Inc. (1986, pp. 27, 30).
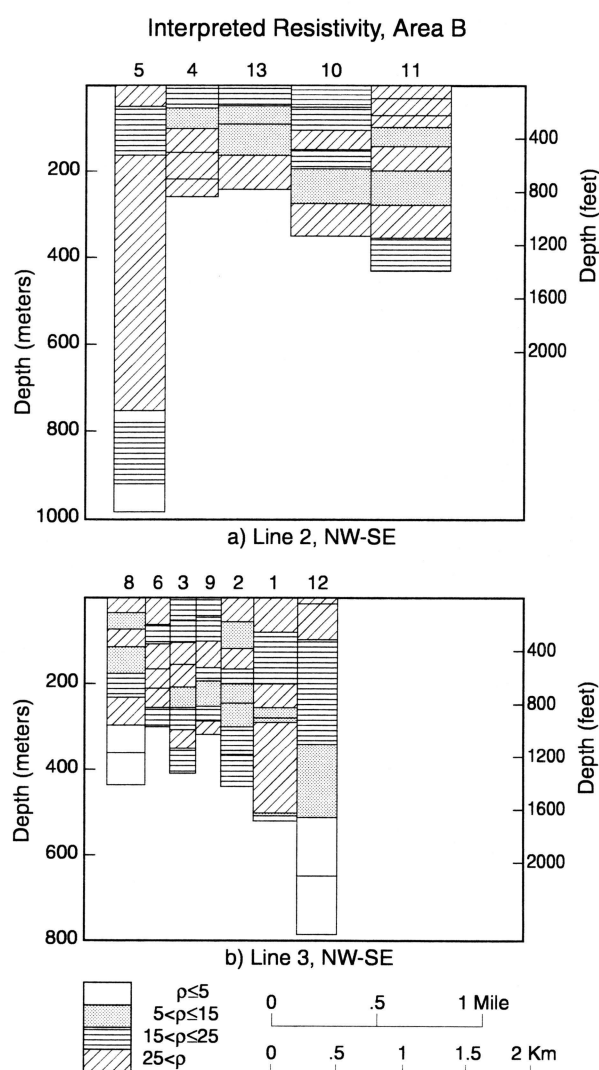
Figure 41: Interpreted resistivity in Area "B." Ranges of apparent resistivity are <=5, 5–15, 15–25, and >25 Ω·m. The lines are shown in Figure 35: (a) line 2, NW-SE, (b) line 3, NW-SE. After Electromagnetic Surveys, Inc. (1986, pp. 28, 29).

Summary: In Area "A," a near-surface conductive zone in Quaternary alluvium deepens toward the lake. It is thickest at station A11, in the Burns Valley schoolyard, where it has a highly conductive zone superimposed in depth. Another deep conductive zone occurs on the southern edge of Burns Valley.

Conductive responses were found across the northern part of Area "B," near stations B5 and B8. They were also found in the southern part of Area "B," near stations B1, B7, and B12. These were considered potential drilling targets. A shallow conductor was located just west of Highway 53, near station B13. This was close to the trace of the Burns Valley Fault and was probably fault-related permeability.

D. Clearlake (Leisek) Wells

Sites were selected for four thermal gradient wells across the geothermal anomaly in Area "A." These were CL-1 to CL-4 in Figure 31. They were sited partly to explore the temperature-radon anomaly, partly to explore the fault intersection predicted by Hearn, Donnelly-Nolan, and Goff (1975), and partly to explore the zone of high flow detected in an offshore survey by Martin (1976) and Martin and Welday (1977) (see Figures 21 and 22).

The geology of the wells is shown in Figure 42. They were drilled by Joseph A. Leisek of New West Exploration. Well CL-1 (API No. 033-90553) was collared at an altitude of 413 m (1,355 ft) on January 23, 1987, and penetrated 8 m (25 ft) of alluvium before passing into a bedrock described as volcanics, presumably Clear Lake Volcanics of Quaternary age, and finished at a depth of 150.9 m (495 ft) on February 3, 1987.

CL-2 (API No. 033-90554) was collared at 418 m (1,370 ft) on February 6, 1987, and penetrated 33 m (110 ft) of alluvium before passing into volcanics, then into Franciscan

formation at a depth of 122 m (400 ft), bottoming at 151 m on February 11, 1987.

CL-3 (API No. 033-90556) was collared at 412 m (1,350 ft) on February 23, 1987, and passed through 37 m (120 ft) before entering the volcanics. It intersected a shear zone 7 m (23 ft) thick at a depth of about 37 m (120 ft). This Cainozoic fault was interpreted as one that is shown trending northwest on the map of Hearn, Donnelly-Nolan, and Goff (1975). The volcanics continued to a depth of 117 m (384 ft) where the well encountered volcaniclastic sediments and finally bottomed at 151 m on March 2, 1987.

CL-4 (API No. 033-90557) was collared at 420 m (1,378 ft) on February 13, 1987, and penetrated 20 m (70 ft) of alluvium before passing into volcanics, bottoming at 151 m on February 23, 1987.

Lost circulation zones were in CL-1 at 331.3–402.9, 299.2–301.9, and 286.3–291.8 m; in CL-2 at 380.8–393.7, 363.4–368.0 m; and in CL-4 at 394.3–398.9, 362.2–364.0, and 327.3–350.3 m.
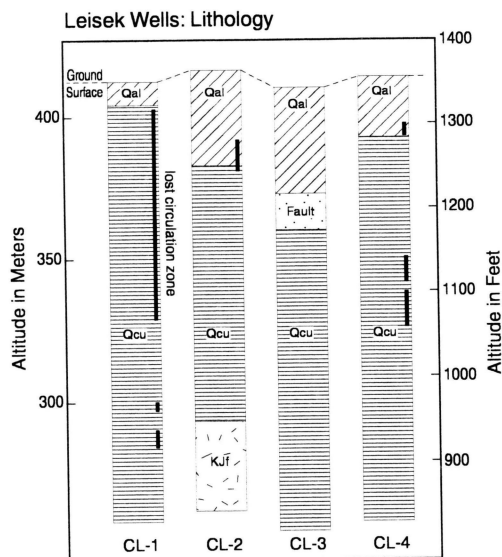
Figure 42: Geology of Leisek wells CL-1, CL-2, CL-3, and CL-4. Qal = Quaternary alluvium; Qcu = Quaternary Clear Lake Volcanics, undifferentiated; KJf = Cretaceous-Jurassic Franciscan formation. After Stone (1987, Figs. 9–12, pp. 52–55).

The temperature distributions in the four Clearlake wells are shown in Figure 43. The spike in CL-3 is an artifact as a result of heat generated by grout used to seal off the fault zone. The last logs were run on April 6, 1987, when it was seen, especially in CL-3 and CL-4, that the drilling transients had died away.

Maximum temperatures encountered during drilling were 32.64°C at 25.9 m (bottom hole) in CL-1, 30.99°C at 144.8 m in CL-2, 26.63°C at 150.9 m (bottom hole) in CL-3, and in CL-4, 35.55°C at 36.6 m.

The geothermal gradient was calculated from linear segments of these temperature curves that were not strongly affected by the plume. The gradient calculated in Clear Lake Volcanics was 35.7 mK/m in CL-1; 113.3 mK/m in CL-2; 87.2, 60.6, and 69.5 mK/m in CL-3; and 85.3 mK/m in CL-4. The gradient in the Franciscan rock was 110.7 mK/m in CL-2. The average for the well field was about 87 mK/m.

The shape of the temperature-depth curves is due to the wells intersecting a zone of hydrothermal circulation. The warmest borehole is

Leisek Wells: Temperature
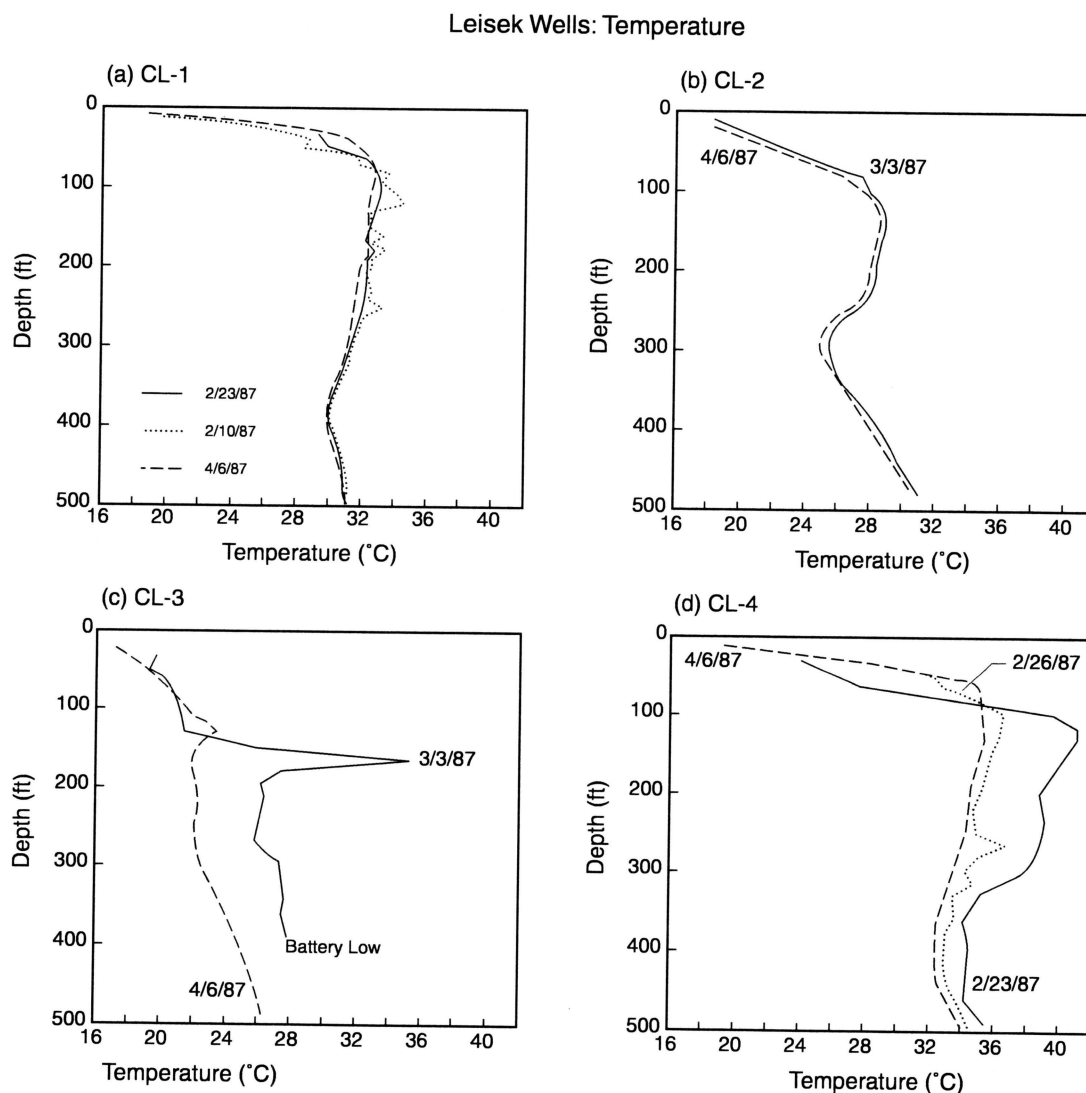
Figure 43: Temperatures of Leisek wells CL-1, CL-2, CL-3, and CL-4. Several different logs were run at different dates in each well. After Stone (1987, Figs. 9–12, pp. 52–55).

CL-4, with a temperature of 36°C. The permeable zone is the fractured upper part of the Clear Lake Volcanics and the contact with the overlying alluvium, at a depth of about 40 m below the ground surface.

E. Natural Tracer Survey

Data were collected from 30 wells in an area along the Burns Valley Creek near the Burns Valley Fault. Table 5 gives results from 21 of the wells.

The mean values of the Na-K-Ca, chalcedony, and quartz geothermometers, respectively, are 45.0°C, 69.8°C, and 99.6°C. These values agree with those obtained previously.

A graph of observed temperature versus well depth is shown in Figure 44. This shows a concentration of temperatures close to 21°C at a depth of 20 m. This is very disappointing as a geothermal source for space heating. The temperatures are higher in deeper wells. The deepest well is 69.5 m, and the temperature increases to 23°C. The regression line shown on the figure has an intercept of 19.1°C and a slope of 59.8 mK/m. The slope is very poorly defined, but that estimate is consistent with the geothermal gradient interpolated from regional information (see Figure 26).
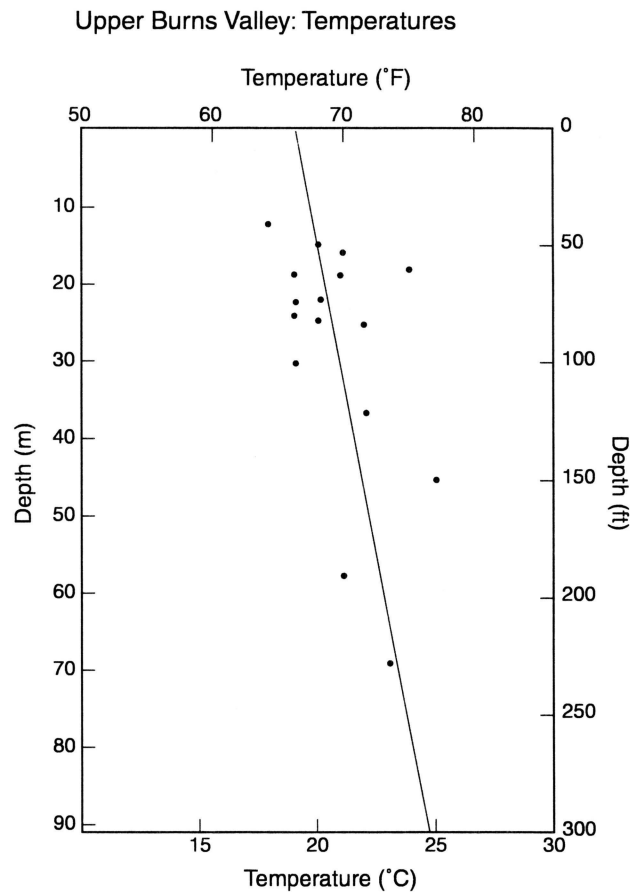
Figure 44: Temperature versus depth, upper Burns Valley. The linear regression shown is $T (mK) = 19.1 + 59.8 \times Z (m)$.

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Sample No.	Depth (ft)	Temp. (°C)	pH	Li (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	F (mg/L)	Cl (mg/L)	B (mg/L)	SiO_2 (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na-K-Ca (β) (°C)	Qch (°C)	Qst (°C)
L23	60	24	6.23	0.26	220	13	140	66	0.3	140	22	110	65	1.3	4/3 73	116	137
L25	52	21	6.74	0.06	40	4.6	42	31	0.5	22	1.2	110	20	BDL	4/3 50	116	137
L44	61	19	6.05	BDL	19	1.5	21	17	0.1	60	0.3	39	17	BDL	4/3 26	60	93
L46	72	20	6.85	BDL	36	2.0	16	12	BDL	13	1.7	60	6	BDL	4/3 44	81	110
L48	--	--	-.--	BDL	22	1.3	32	30	0.2	16	0.2	20	33	310	4/3 18	31	69
L57	83	22	6.28	BDL	27	1.5	37	21	BDL	80	0.5	37	40	BDL	4/3 20	57	91
L59	--	--	-.--	BDL	27	2.1	33	30	0.2	17	0.9	BDL	14	220	4/3 30	-.-	--.-
L64	--	--	-.--	0.32	110	7.4	130	68	0.4	1400	12	BDL	BDL	460	4/3 51	--.-	--.-
L70	150	25	7.10	BDL	21	2.9	40	14	0.2	23	0.5	39	14	1.2	4/3 33	60	93
L75	120	22	5.08	BDL	26	8.8	17	15	0.2	1.0	0.1	44	23	BDL	4/3 83	66	97
L77	--	--	-.--	0.10	42	5.1	110	48	0.4	28	2.3	BDL	BDL	610	4/3 36	--.-	--.-
L78	100	19	6.70	0.04	23	3.1	32	18	0.4	17	0.4	35	15	BDL	4/3 39	55	89
L86	50	20	6.13	BDL	19	1.6	21	15	BDL	63	0.2	25	130	BDL	4/3 28	40	77
L89	190	21	7.01	0.15	240	10	78	41	0.4	28	3.5	19	700	1.1	4/3 78	29	67
L135	--	--	-.--	0.03	29	3.3	30	35	0.4	21	0.4	BDL	29	290	4/3 44	--.-	--.-
L170	40	18	6.45	BDL	17	1.4	19	13	BDL	23	0.2	25	40	BDL	4/3 26	40	77
L171	72	19	6.44	BDL	22	1.8	20	13	0.2	12	0.5	44	52	BDL	4/3 33	66	97
L174	80	19	6.78	BDL	44	3.0	20	15	0.4	10	1.7	100	14	BDL	4/3 52	110	133
L176	228	23	6.97	BDL	99	6.4	30	39	0.3	8.0	5.5	86	15	BDL	4/3 75	101	126
L199	72	20	6.81	BDL	37	2.1	18	12	0.1	18	1.4	39	21	BDL	4/3 43	60	93
L200	61	21	6.49	0.07	42	7.0	50	42	0.4	34	1.3	78	BDL	BDL	4/3 59	96	121

Table 5: Analyses of domestic well waters, Burns Valley. Measures are metric except for depth (in feet). Locations were confidential. TDS = total dissolved solids. BDL = below detectable limit. After Anonymous (1990, Tab. 1). Geothermometers calculated after Fournier (1977, p. 44).

The most interesting results were obtained by showing the concentrations of chlorine, fluorine, and boron on a map (Figure 45). The elongated concentrations correlate with the Burns Valley Fault, indicating a source for the geothermal water in resurgences along the fault.

It has been suggested that the intake for meteoric waters is on Quackenbush Mountain to the east. Burns, Potter, and Zyvoloski (1992) suggested instead that the intake is to the northwest. They suggested that meteoric waters are conducted down the thrust fault on Bald Mountain to a depth of about 610 m (2,000 ft), where the thrust is intersected by the Burns Valley Fault, and then become resurgent at the Burns Valley Fault. The ground temperature at the lowest point on that path would be about 61°C above the surface temperature, or 74°C, which agrees generally with the geothermometric predictions of resource temperature in Table 5.

a) Boron Contours in ppm

b) Chloride Contours in 10 ppm

c) Silica Contours in 10 ppm
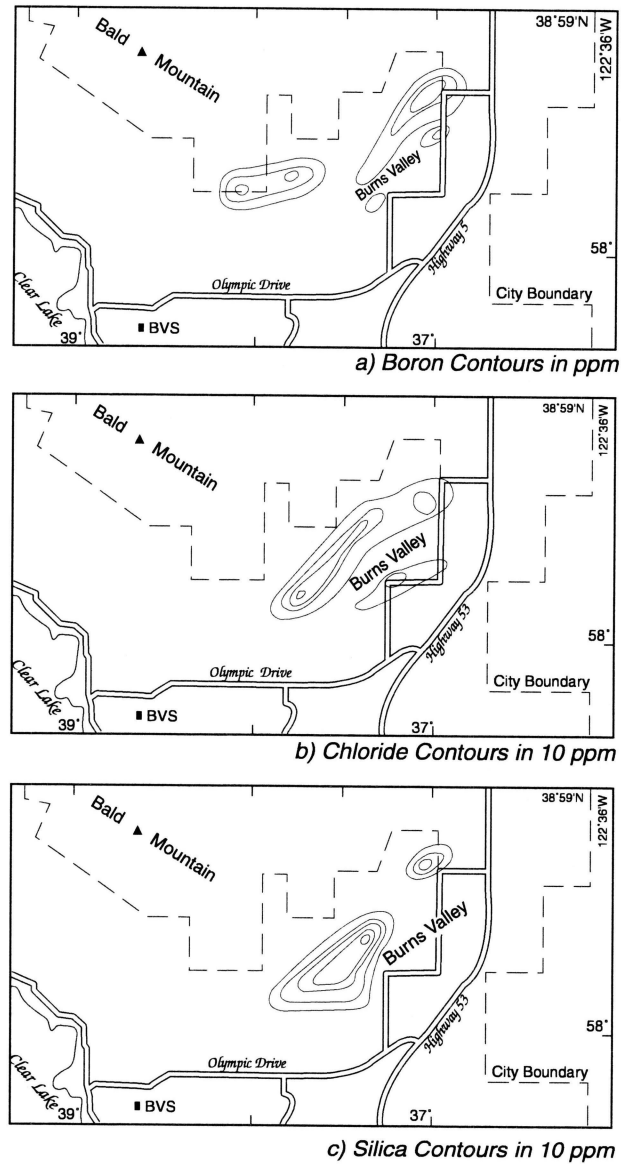
Figure 45: Maps of concentrations of boron, chloride, and silica in Burns Valley. (a) boron, contours 0-1-2-3 mg/L; (b) chloride, contours 0-10-20-30 mg/L; (c) silica, contours 0-10-20-30-40 mg/L. Compiled by Anonymous (1990).

VIII. THE HOT SPRING AT SULPHUR BANK MINE

A. General Description of Sulphur Bank Mine Area

Location: The Sulphur Bank Mine occupies about 324 ha (800 acres), mainly in T13N R7W, Sec. 6, on the south shore of Oaks Arm of Clear Lake (Figure 46). It is outside the limits of the City of Clearlake, but sufficently close to be included in the city's resources. There have been several tests of the geothermal potential of the area.
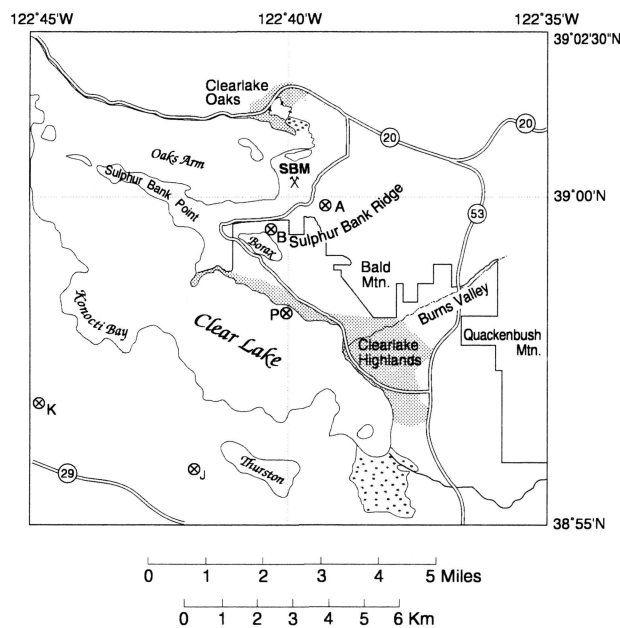
Figure 46: Locality map of the region adjoining the City of Clearlake. SBM = Sulphur Bank Mine, P = Oak Cove. Deep wells are A = Audrey, B = Borax Lake, J = Jorgensen, and K = Kettenhofen. From Burns, Potter, and Zyvoloski (1992, Fig. 2, p. 136).

Sulphur Bank Mine Geology: The geology of the Sulphur Bank Mine area is shown in the map of Figure 47. The mine area is underlain by Jurassic Franciscan rocks, comprising greywacke (KJ$_f$) and chert (Ch). The southeast corner of the map is part of Sulphur Bank Ridge and is composed of Franciscan green-

stones (V). The greenstones are thrust over the greywacke-chert assemblage on a fault that trends southwest-northeast across the corner of the map.

The Franciscan basement is overlain by a thin sequence of Quaternary lake sediments (Q$_l$). Overlying this is a Quaternary andesitic assemblage (Q$_{ca}$), comprising tuffs and flows. The andesite flow is dated at 44.5 ka (44,500 yr) (F. Goff, personal communication). The source of the andesite appears to be vents now covered by lava (Anderson, 1936, p. 649). A volcanic pipe in the northeast corner of the map is now occupied by a basaltic cinder cone (Qcbp), the southernmost of the three northern cones that were shown in Figure 17.
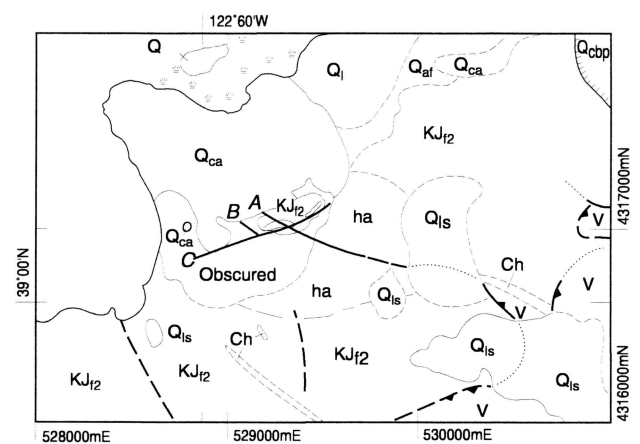
Figure 47: Geological map of the Sulphur Bank Mine area. Modified from Burns, Potter, and Zyvoloski (1992, Fig. 5, p. 138). KJ$_{f2}$ = Franciscan sediments, mainly argillite and sandstone; Ch = distinctive chert bands; V = Franciscan volcanics, mainly basalt; Q$_{ca}$ = andesite flow; Q$_l$ = Quaternary lake deposits; Q$_{ls}$ = Quaternary landslide deposits; ha = hydrothermally altered Franciscan argillite. The cross-hatching is breccia. A, B, and C are faults.

The andesite is overlain by Quaternary alluvium (Q_{al}), and landslide debris (Q_{ls}). Franciscan basement rocks are hydrothermally altered (ha) in the vicinity of the mine.

Sulphur Bank Mine faults: The spring is fault controlled. Everhart (1946, p. 137, and mine maps in Pl. 21 and Pl. 22) described three faults, "A," "B," and "C," as shown in Figure 48.
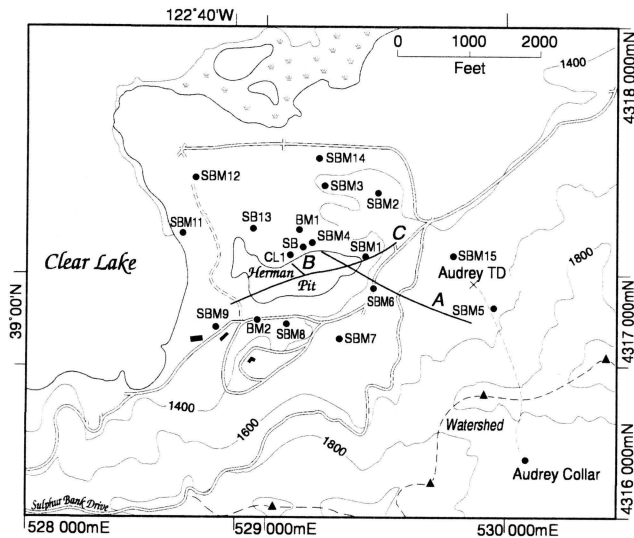
Figure 48: Map of faults and exploration wells near Sulphur Bank Mine. A, B, and C are faults described in the text. Exploration wells are SB-1 = Sulphur Bank 1, CL-1 = Clearlake 1, BM-1 to BM-2 = Bradley Mining Company 1 to 2, SBM-1 to SBM-15 = Sulphur Bank Mine 1 to 15. From the records of the California Division of Oil and Gas. For the Audrey well, the collar is shown, after Richter (1981); also the track of the hole, projected to the surface, after Beall (1985).

(A) northwest-trending: Fault "A" trends about N295E. It dips steeply to the northeast, has dextral displacement, and can be traced from Herman's pit for a distance of a mile to the southeast. A line of small agglutinate vents trends N295E from the mined area at Sulphur Bank to Rattlesnake Island (Everhart, 1946, p. 135), possibly marking the trace of the fault. An analysis of Everhart's mine map (Everhart, 1946, Pl. 22), yields a representative strike of N302E and dip of 80° to the northeast. This is a dextral (right-lateral) transcurrent fault.

(B) northwest-trending: A fault exposed 122 m (400 ft) west of fault "A" strikes about N315E and dips vertically. This fault has moved quite recently. It displaces recent sediments and andesite, with the northeast side moved upward 9 m (30 ft) and to the southeast for 15 m (50 ft). An analysis of three similar faults on Everhart's mine map (Everhart, 1946, Pl. 22), yields a representative strike of N334E and dip near vertical.

(C) northeast-trending: A fault trends about N70E along the axis of Herman pit, dips to the southeast, and has reverse displacement. Averill (1946, p. 35) described it as thrust fault dipping north, but this is an error. An analysis of three similar faults on Everhart's mine map (Everhart, 1946, Pl. 22), yields a representative strike of N066E and dip of 58° to the southeast. The dip is greater than 45°, so this is not strictly a thrust, but a reverse fault.

Hearn, McLaughlin, and Donnelly-Nolan (1988, Fig. 3, p. 17) recognized a major arcuate fault that runs along the southern side of Oaks Arm. It is marked offshore by gaseous springs (Sims and Rymer, 1976). If the fault is projected onshore along strike, it passes through the mine area. However, its relationship to the other faults is problematical. It does not match any of "A," "B," or "C," in either trend or displacement.

Hydrothermal manifestations: The underground workings of the Sulphur Bank Mine were noted for their high underground temperatures. According to Averill (1946, p. 35) work was restricted to 20-minute shifts and the men were constantly sprayed with water while underground.

Averill (1946) reported that boiling hot springs were numerous, and in one case action was so violent that a continual spray of mud and water was thrown into the air. The temperature of waters reaching the surface averages about

55°C. Everhart (1946, p. 13) cited temperatures of 43°C, 52°C, 36°C, and 53°C. White and Roberson (1962, Tab. 1, p. 412) cited temperatures for a spring in Canal pit of 80.5°C, and for springs in various parts of Herman pit of 44°C, 47°C, 57°C (Ink spring), and 69.5°C ("geysers" spring). They reported (Tab. 2, p. 414) measuring temperatures of 47°C and 77°C for springs and 69.5°C for the "geyser."

Everhart (1946, p. 141) said that solfataric activity was scattered along the northeast-trending fault "C," with the greatest activity near the intersection with the northwest-trending fault "B." Beall (1985) said spring activity was concentrated on an east-west zone of gas leakage. Because shallow temperature gradients did not indicate any particular fault control, Beall (1985) thought the spring was controlled by a pipe of low permeability at the fault intersection, giving rise to a linear pipe with circularly symmetric heat flow.

Geochemistry: The hydrothermal waters at Sulphur Bank Mine are exceptionally high in carbon dioxide, boron, ammonia, sodium, and iodine and are low in silica and potassium (White and Roberson, 1962). The ammonia content of 460 ppm was near the maximum that had been recorded in natural waters. The boron content of 620 ppm is nearly equal to the chlorine concentration (White, 1967).

The most notable characteristics of the Sulphur Bank spring waters are the very high content of ammonia, bicarbonate, and boron; the low silica; the low ratio of potassium to sodium; and high ratios of iodine to chlorine and boron to chlorine. In addition to the dominant carbon dioxide, gases include abundant methane (White and Roberson, 1962).

Total natural discharge of deep water, calculated to a chlorine content of 640 ppm is about 200 L/min (White, 1967), or 50 gal./min (White and Roberson, 1962).

The Sulphur Bank waters are nonmeteoric, of the low-chloride type, and tend to be relatively enriched in bicarbonate (Beall, 1985). White, Barnes, and O'Neil (1973) suggest the source is metamorphic water. The heat is probably volcanic heat (White and Roberson, 1962), transferred by conduction to the geothermal fluid.

Mineralization: White and Roberson (1962, p. 398) said that Sulphur Bank Mine is the most productive mineral deposit in the world that is clearly related genetically to hot springs. The total production was 4.7 million kg of mercury, the fourth largest mercury mine in the United States.

Sulphur and mercury mineralization at Sulphur Bank Mine is closely related to the geothermal activity. At the water table, a vapor phase relatively rich in H_2S separates from liquid water, and near the surface, the H_2S oxidizes to native sulphur and sulphuric acid. Leaching by sulphuric acid above and near the water table produces a suite of minerals, including cinnabar and soluble sulphates.

The ore was localized to a major extent immediately below the water table that existed before mining. Characteristic minerals included cinnabar, marcasite, pyrite, metacinnabar, stibnite, calcite, dolomite, quartz, and buddingtonite (White, 1967). Buddingtonite, an ammonium aluminosilicate, was first discovered at Sulphur Bank Mine by Erd, White, Fahey, and Lee (1964). Because of the distinctive spectral signature, ammonium feldspar has become important in wide-area mineral exploration.

It was reported that mineralization is proceeding at the present time in many of the springs and steam vents. Waters and gases still transport mercury and antimony. Cinnabar deposits coat some surfaces in the quarries (Averill, 1946, p. 35; White, 1967).

The mercury mineralization suggests vapor transport. Cinnabar is unstable below 584°C and breaks down into mercury and sulphur vapors. Temperatures of 125°C to 150°C may be sufficiently high to transport significant quantities of quicksilver in vapor if the proportion of vapor to liquid is high. The isotopic evidence indicates that temperatures near the surface were formerly somewhat above present temperatures. If the temperature at depth had been close to the boiling point for pure water, quicksilver could have been transported in a vapor phase, condensing in associated water near the surface. The amount of quicksilver in Sulphur Bank fluids is estimated to be in the range 0.04 to 7 mg/L, most probably 0.1 to 1.0 mg/L (White and Roberson, 1962).

Mineral production: The early history of the mine dates back to 1865 when the California Borax Company began to exploit the free sulphur. Operations ceased in 1868. Production of quicksilver began in 1873 and continued until 1897. Underground mining was carried on from about 1880 to 1897 despite high temperatures and objectionable gases. Ore was then mined from open pits from 1899 to 1902, 1915 to 1918, and on a larger scale, 1927 to 1947, and 1955 to 1957. The total production of mercury was 4.7 million kg, making it the fourth largest producer of mercury in the United States (White and Roberson, 1962). The mine is currently inactive.

It had quite extensive underground workings that followed mercury veins. When the pumps were stopped, hot water flooded the mine and the shafts are now the site of hot-water resurgences. Analyses by Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973, p. A15) showed mercury concentrations in a flowing well to be 1.5 µg/L, well below the maximum considered safe for drinking water by the U.S. Public Health Service. The mercury in Wilbur Springs and at the Abbott Mine was shown to

be deposited within a few meters of spring orifices (ibid., p. A16), and presumably so at Sulphur Bank.

Nevertheless, there have been concerns about mercury entering Clear Lake from the mine. An investigation showed the principal danger was from particles of solid mercury removed by wave action from dumps of mine material (Chamberlin, Chaney, Finney, Hood, Lehman, McKee, and Willis, 1990). Construction or modification of a retaining wall along the lake shore was proposed to prevent erosion of mine material.

B. Exploration of Sulphur Bank Mine Area

Exploration drillholes: The locations of wells drilled near the Sulphur Bank Mine are shown in Figure 48 and Table 6. In the following descriptions, Section 5 refers to Township 13 N, Range 7 W, Mount Diablo Baseline and Meridian. Please note that in this section, VIII.B, measurements are given in the same units as the source document, and conversions from feet to meters are omitted. Elevations are above mean sea level.

Exploratory well SB-1: "Sulphur Bank No.1" (API 033-90011) was drilled by the Sulphur Bank Geothermal Power Company of R. A. Rowan and Co., Los Angeles. White and Roberson (1962) said Magma Power Company was a joint venturer. The well was also known as "Magma No.1" (Zimmerman, 1975c, p. 12 and Fig. 5).

Barger (1967) noted that the well was located 1,180 ft E and 2,920 ft S from the NW corner of Sec. 5, with a collar elevation of 1,340 ft and a total depth of 528 ft. Allen (1971) placed the well 4,100 ft W and 3,100 ft S from the NE corner of Sec. 5, with a collar elevation of 1,260 ft and a total depth of 510 ft.

Well Name	API Number	Drilling Started	Completion Date	Depth (ft)	Origin (Sec. 5)	East (ft)	North (ft)	Temp. 100 ft (°F)	Temp. Gradient (mK/m)	GW Gradient (mK/m)
SB-1	033-90011	Unknown	Unknown	528	NE	4161W	2941S	---	---	---
CL-1	033-90008	Dec. 12	Jan. 10, 1962	1413	NE	4423W	3004S	---	448	410
BM-1	033-90006	May 01	June 14, 1964	2089	NE	4258W	2720S	410.	448	---
BM-2	033-90007	June 17	July 28, 1964	3985	NE	4920W	3845S	---	217	160
SBM-01	033-90580	June 01	June 01, 1980	105	SW	1890E	2220N	103.1	630	630
SBM-02	033-90581	June 09	June 09, 1980	105	SW	2020E	2950N	98.1	453	170
SBM-03a	033-90582	May 25	hole collapsed	---	---	---	---	---	---	---
SBM-03b	033-90582	June 10	June 10, 1980	105	SW	1270E	3080N	105.6	702	190
SBM-04	033-90583	May 22	May 25, 1980	105	SW	1190E	2340N	56.3	1178	440
SBM-05	033-90584	May 19	May 20, 1980	100	SW	3630E	1500N	78.6	193	190
SBM-06	033-90585	June 02	June 03, 1980	105	SW	2000E	1720N	86.0	297	300
SBM-07	033-90586	June 10	June 11, 1980	105	SW	1540E	1080N	80.2	---	---
SBM-08a	033-90587	June 03	hole collapsed	---	---	---	---	---	---	---
SBM-08b	033-90587	June 07	June 07, 1980	105	SW	0820E	1300N	92.8	350	175
SBM-09	033-90588	May 30	May 31, 1980	90	SW	0130W	1250N	86.2	312	155
SBM-10	033-90589	May 31	hole collapsed	---	---	0025E	1790N	---	---	---
SBM-11	033-90590	June 07	June 08, 1980	105	SW	0580W	2500N	---	389	---
SBM-12	033-90591	June 11	June 13, 1980	105	SW	0400W	3230N	91.4	426	160
SBM-13	033-90592	June 03	June 04, 1980	105	SW	0360E	2550N	105.6	509	190
SBM-14	033-90593	May 21	hole collapsed	---	SW	1190E	3460N	---	---	---
SBM-15	033-90594	May 21	May 21, 1980	95	SW	3110E	2240N	84.0	344	185
Audrey 1	033-90287	Oct. 31	May 22, 1981	10042	SE	1082W	853S	---	141	---

Table 6: Exploration wells at the Sulphur Bank Mine. The eastings and northings are with respect to an origin at one of the corner points of Sec. 5, R7W, 13N, Mount Diablo Baseline and Meridian. The locations of SB, CL, and BM wells are from O'Connor (1964). The drilling dates for SBM wells are from Beall (September 1980). The locations of the SBM wells are from Beall (October 1980). The location of Audrey well is from Richter (1981). The temperature at a depth of 100 ft is from Beall (1985, Fig. 8, p. 399). The geothermal gradient is calculated from regression on the deepest linear portion of wire-line temperature logs. The "GW gradient" is the geothermal gradient normalized to greywacke, calculated by R. Potter, using thermal conductivities of 1.6 W/m·K for Quaternary alluvium, 1.2 W/m·K for Quaternary andesite, and 3.22 W/m·K for Franciscan greywacke.

Zajac (1971) gave the depth as 546 ft. Anderson (1971b) noted the well location as 100 ft E of Bradley Mining 1 well. Reed (1973a, 1973c) placed the well 1,180 ft E and 2,920 ft S from the NW corner of Sec. 5, with a collar elevation of 1,340.4 ft and a total depth of 528 ft. The NW corner post of Sec. 5 is unsurveyable, being located under the waters of Oaks Arm. The well location on Figure 48 is from a stadia survey by O'Connor (1964), with origin at the midnorth line of Sec. 5; this is approximately 4,161 ft W and 2,941 ft S from the NE corner of Sec. 5.

The date of drilling is unknown; the well was formally abandoned on June 30, 1971.

White and Roberson (1962) recorded bottom-hole temperatures of 79°C at 134 ft, 110°C at 390 ft, and 135.5°C at 528 ft. Zimmerman (1975c, Fig. 5) shows the following bottom-hole temperatures at approximate depths: 77°C at 150 ft; 111°C at 386 ft; and 133°C at 553 ft for "Magma No. 1."

Zimmerman (1975c, p. 12) reported that the wells SB-1, CL-1, BM-1, and BM-2 hit shallow horizons bearing carbon dioxide and produced hot water with 5% steam flashover. Anderson (1971a) reported that on March 10, 1971, Sulphur Bank No. 1 well was unloading periodically, at intervals of two to three minutes, and ejecting hot water about 15 ft into the air together with a large volume of steam.

Exploratory well CL-1: Clear Lake No. 1 [American Petroleum Institute (API) 033-90008] was drilled by Hawaii Thermal Power Company and Magma Power Company. The well was termed "Magma No. 2" in Zimmerman (1975c, p. 12 and Fig. 5).

The location was determined by O'Connor (1964), by stadia survey, with origin at the midnorth line of Sec. 5; this is approximately 4,423 ft W and 3,004 ft S from the NE corner

of Sec. 5. Reed (1973b) gave the location as 910 ft E and 2,980 ft S from the NW corner of Sec. 5. The location on Figure 48 is after Reed (1973b).

The well was drilled between December 13, 1961, and January 10, 1962, to a depth of 1,413 ft and a temperature of 197°C. Zimmerman (1975c, p. 12) reported a temperature of 186°C at 1,391 ft in 1974.

The flow line temperatures, usually an underestimate of the true gradient, yield a gradient of 389 mK/m. Bottom-hole temperatures from the drillers log yield a geothermal gradient of 448 mK/m (Figure 49).
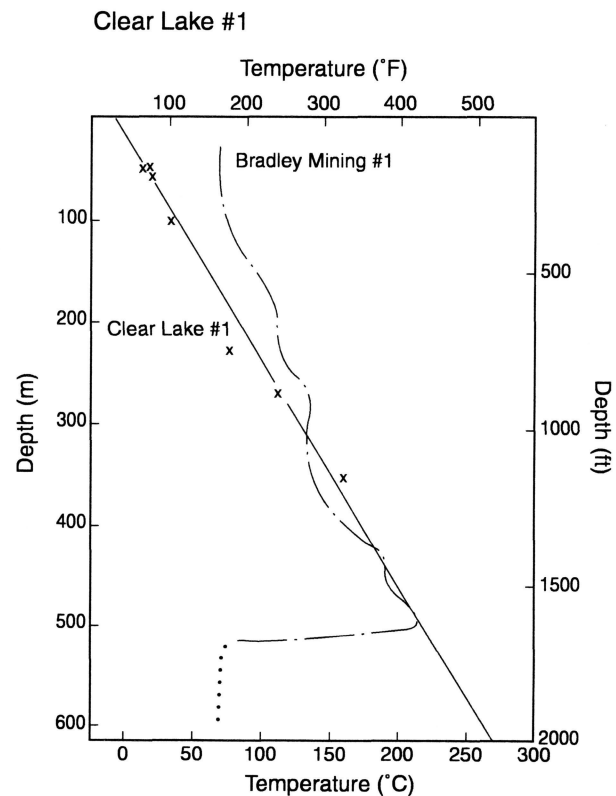

Figure 49: Temperatures at depth in Clear Lake No. 1 and Bradley Mining 1 wells. The estimated geothermal gradient from the Clear Lake 1 data is 448 mK/m, as shown by the straight line. The temperature log for the Bradley Mining 1 well shows the lingering effects of inflow of fluid at 218°C from a fracture at a depth of 514 m.

Exploratory wells BM 1 and 2: The wells "Bradley Mining Company" Nos. 1 and 2 were drilled by Earth Energy, Inc.

The well locations in Figure 48 are after O'Connor (1964), by stadia survey, with origin at the midnorth line of Sec. 5. According to that survey, the BM-1 well was approximately 4,258 ft W and 2,720 ft S, and the BM-2 well was approximately 4,920 ft W and 3,845 ft S from the NE corner of Sec. 5. Otte (1967) placed BM-1 1,330 ft E and 2,300 ft N, and placed BM-2 600 ft E and 1450 ft N from the SW corner of Sec. 5.

Well BM-1 (API 033-90006) was drilled between May 1 and June 14, 1964, collared at 1,376 ft, and reached a depth of 2,089 ft.

The well hit a crevice 0.3 m (1 ft) wide at 501.4 m (1,645 ft). A flow test was conducted from May 23 to 30, which yielded a mixture of water and steam, at temperatures up to 330°C. The maximum flow rates were approximately 8.8 kg/s (70,000 lb/h) for steam and 214.2 kg/s (1,700,000 lb/h) for water, at a wellhead pressure of 1.2 MPa (180 psi).

On June 12, the well was allowed to flow for 15 h from the fracture at a depth of 501 m; the temperature survey of Figure 49 was made after the well had been held static for 13.5 h. The flowing temperature gradient is about 300 mK/m, about 67% of the conductive gradient found in the Clear Lake No. 1, because of convective heat transfer up the well.

The temperature at the flowing aperture was measured on May 26, after a 13-hour shut-in, as 208°C (407°F); a log made on June 12 found 218°C (424°F). The fluid inlet temperature for BM-1 agrees with the geothermal gradient at that depth as measured in the Clearlake No. 1 well.

Figure 49 shows temperature profiles in two wells at the site. The straight line fitted to measurements in Clear Lake No. 1 represents a gradient of 410°C/km. The other line is a temperature log in Bradley Mining Co. No. 1 after two campaigns of flow testing and redrilling. The log was taken after the well had been static for 13.5 h. There were flowing fractures at 1,421 ft and 1,645 ft. The upper part of the log reflects flow up the wellbore from those fractures. The lower part of the log, below 1,645 ft, is thought to be in cold mud introduced into the hole during the redrilling.

Well BM-2 (API 033-90007) was drilled between June 17 and July 28, 1964, collared at 1,376 ft, reaching a depth of 3,985 ft and a temperature of 302°C.

A well test yielded a flow of water and steam for less than 6 h; the maximum flow rate was 151.4 L/s (40 gal./min). Temperature logs were run on July 10, after a 16-h shut-in, and on July 25, after the hole was static for 23 h. The results are shown in Figure 50. The geothermal gradient estimated from the log of July 25 is shown by the straight line; the slope is 217 mK/m. This gradient agrees with bottom-hole temperatures measured during drilling.

Geothermal gradient wells SBM 1 to 15: In 1980, a series of shallow wells, "Sulphur Bank Mine" Nos. 1 through 15, were drilled to determine the geothermal gradient in the near-surface. API numbers were 003-90580 to 033-90594.

The well locations were described by Beall (April, September 1980) and shown in Beall (1985, Fig. 8, p. 399). The locations shown in Figure 48 are from Beall (April, September 1980).

Deep exploration well Audrey A-1: The Audrey A-1 well (API No. 033-90287) was drilled by Phillips Petroleum Company in the period of October 31, 1980, to May 22, 1981.
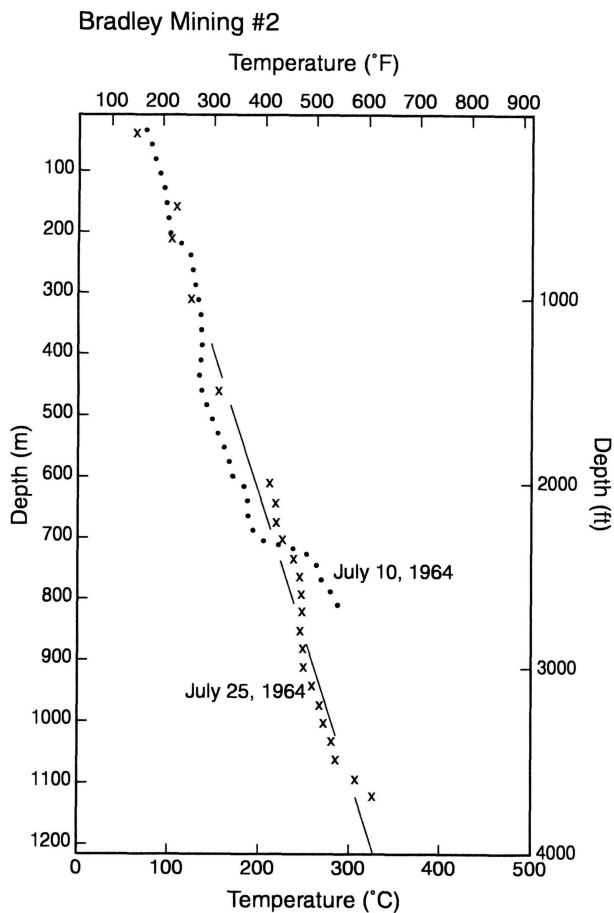
Bradley Mining #2

Figure 50: Temperatures at depth for the Bradley Mining 2 well. The estimated geothermal gradient is 217 mK/m, as shown by the straight line.

The well was collared at an altitude of 516.03 m and reached a depth of 3,060.8 m (10,042 ft). The records of the Division of Oil and Gas provide nine different collar locations, as listed below in offsets from the NE corner of Sec. 8 T13N R7W, which is the same point on the ground as the SE corner of Sec. 5 T13N R7W.

Acronyms are: (KB = kelly bushing, GL = ground level, asl = above mean sea level, TD = total depth).

(1) Drill pad elevation approximately 1,700 ft, bottom elevation of waste sump approximately 1,685 ft (Audrey site plan, March 4, 1980, Patterson, 1980a).

(2) 260 m S, 330 m W, GL 512 m asl (Notice of Intention to Drill, March 11, 1980, Patterson, 1980b).

(3) 700 ft S, 1200 ft W (Daily Report Detailed for November 1, 1980, Patterson, 1981b).

(4) 813 ft S, 1,344 ft W GL 1,693 ft asl (Schlumberger log, December 18, 1980, Finnell, 1980).

(5) 611.65 ft S, 1,252.59 ft W, GL 516.03 m asl, (survey, January 22, 1981, Richter, 1981, elevation from Reese, 1983).

(6) 611.65 ft S, 1,252.59 ft W, GL 1,693 ft asl (Log Quality Check List, February 5, 1981, Finnell, 1981).

(7) 612 ft S, 1,253 ft W, GL 1,695 ft asl (Well Summary Report, July 22, 1981, Patterson, 1981a).

(8) 853 ft S, 1,082 ft W, KB 1,717 ft asl, TD 10,042 ft (Individual Well Record, April 19, 1982, U.S. Geological Survey, 1982).

(9) 700 ft S, 1,200 ft W, GL 516.03 m asl, TD 3061 m (Well Summary Report, June 8, 1983, Reese, 1983).

The location adopted in Figure 48 is that surveyed by Richter (1981). This differs from Beall (1985, Fig. 8, p. 399) by about 400 ft.

The hole deviated strongly and ended up at depth only 2,200 ft in plan from the collar of BM-1 well. The track in the subsurface shown in Figure 48 is modified from that shown in Beall (1985, Fig. 1, p. 396).

The well is thought to have intersected at depth the major fault "A" trending southeast through Sulphur Bank. The driller encountered problems in silica carbonate rock between 7,500 and 8,000 ft, which are thought to have been due to a sliver of hydrothermally altered serpentinite plugging the fault. This is not unexpected on large strike-slip faults; for example, there is another sliver (of greenstone) in a parallel fault near Borax Lake.

Temperature measurements made at different times are shown in Figure 51. Five sets of measurements are known. The data of December 19, 1980, are from the first wire-line log made when drilling had reached a depth of 1,540.8 m (5,055 ft). A cluster of five thermometers on the bottom averaged 122.2°C (252°F), and 2 h later (about 23 h after circulation stopped) they averaged 138.9°C (282°F). The gradient estimated from this measurement is 90.1 mK/m, the same order of magnitude as Borax Lake and the Jorgensen and Bradley MC-2 wells.

The data of January 18, 1981, are from a second wire-line log run after milling junk, when drilling had reached a depth of 7,913 ft. The maximum temperature on the then bottom was 436°F and after 15 minutes, 440°F.

The data of April 8, 1981, are from a third wire-line log run after the hole had been static for 65 days. The operator thought the depths of the last few points were not correct because the tool had slowed down in mud. The maximum temperature reached, at point "B," was 532°F at a depth of 6,224 ft (see also Beall, 1985, Fig. 7, p. 398). The line "AB" has a slope of 141.5 mK/m. This is the best available estimate of the geothermal gradient in the Audrey A-1 well.

The well was at 9,500 ft on February 9, 1981. On May 22, 1981, it was unloaded and allowed to flow. A fourth wire-line log was made on June 5, 1981, while the well was flowing. The hole had been flowing about 10,000 lb/h of steam for 15 days. The flow was from fissures and pore spaces in communication with the well. The flow cooled the well, because of the latent heat of vaporization, and the resulting curve approximates the steam temperature line.
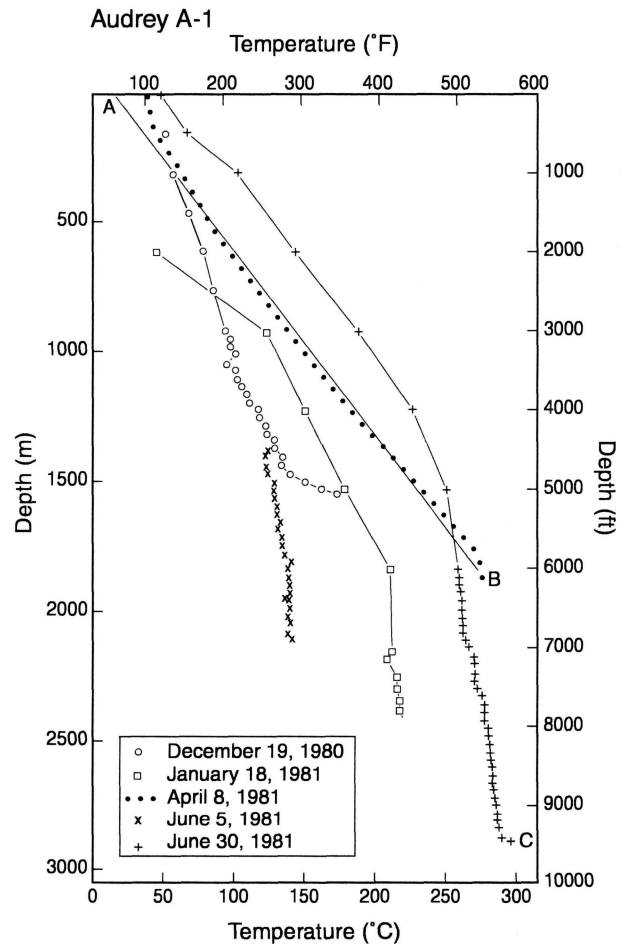

Figure 51: Temperatures at depth in the Audrey A-1 wildcat well.

The well was again shut in, and a fifth wire-line log run on June 30, 1981, while the well was on a slow bleed. The maximum temperature, at point "C," was 567°F at 9,465 ft (see also Beall, 1985, Fig. 7, p. 398). This time the well above 5,000 ft is superheated compared to the normal conductive gradient. This is interpreted as water at 630°F entering the hole at 9,000 ft, flashing to steam, and convecting in the lower part of the hole.

The graph of temperature versus depth for April 8, 1981, is concave upwards. This may be due to changes in the conductivity of the wellbore rocks. R. M. Potter, from a statistical analysis of temperature differences, estimated that the geothermal gradient, T (mK/m), was a function of depth Z (m), according to $T = 95.3 + 0.0489 \times Z$. A nonequilibrium thermal condition of this type was found in well HV39 at The Geysers by Williams, Galanis, Moses, and Grubb (1993), who attributed it to conductivity variations in a region of uniform heat flow.

Well Audrey A 1-A: This well (API no. 033-90288) was proposed on February 21, 1980, and was cancelled by August 30, 1985.

C. Characterization of the Resource

Geothermal gradients at Sulphur Bank Mine: There is a well-defined geothermal anomaly centered on the hot spring. It was defined by a series of wells as tabulated in Table 6 and interpolated on the contour map of Figure 52.

The background geothermal gradient is about 100 mK/m. The geothermal anomaly caused by the hot spring is the heat flow in excess of the background. By integrating the map of Figure 52, the conductive heat flow is estimated at 0.57 MWt. The spring flows at about 1 L/s (15 gal./min) at a temperature of 42°C. The heat carried by the hot water is

0.239 MWt. R. M. Potter estimated the total of conductive and hydrothermal heat flow at 0.81 MWt.
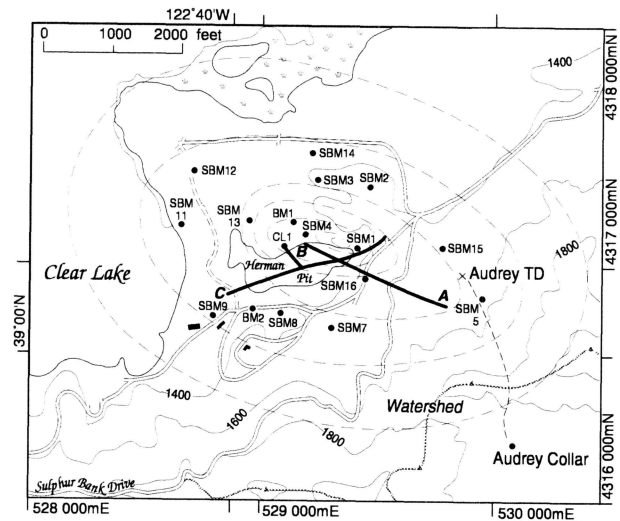
Figure 52: Map of the geothermal gradient near Sulphur Bank hot spring. Compiled by R. Potter. From Burns and Potter (1993, Fig. 7, p. 320).

We consider that the geothermal anomaly at Sulphur Bank Mine is a concave "spike" about 610 m (2,000 ft) in diameter. A cross section is shown in Figure 27.

Geochemistry of waters near Sulphur Bank Mine: The geochemical data for geothermal waters in the Sulphur Bank Mine area are tabulated in Table 7, along with similar waters in the region.

Physical conditions in Sulphur Bank Mine spring: The natural conditions at depth were studied by Burns, Potter, and Zyvoloski (1992) as part of this project. Their conclusions are shown in Figures 53 and 54. There is a liquid-dominated heat pipe ascending to about 732 m (2,400 ft), above which rests a condensed water cap.

No.	Temp (°C)	pH	Li (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	F (mg/L)	Cl (mg/L)	B (mg/L)	HCO$_3$ (mg/L)	NH$_4$ (mg/L)	SiO$_2$ (mg/L)	SO$_4$ (mg/L)	Na-K-Ca (β)	(°C)	Qch (°C)	Qst (°C)
1	99	8.1		1340	44	26	23		900	828	2600	354	203	680	1/3	157	160	169
2	85	7.95		1310	41	19	40		782	620	2090	490	140	1630	1/3	156	133	149
3	87	7.0		1390	68	56	57	2	489	528	1890	543	67	1940	1/3	171	87	115
4	22	6.6	---	770	70	2	BDL	BDL	990	500	1420	BDL	138	10	1/3	228	132	148
5	--	7.9	---	2580	25	5	4	BDL	195	1300	2450	BDL	60	70	1/3	124	81	110
6	--	8.8	0.2	1100	22	6.9	7.3	0.6	90	6	2000	2	---	550	1/3	141	---	---
7	--	8.2	4.0	1100	51	28	11	1.1	741	690	1300	310	---	530	1/3	170	---	---
8	--	8.5	1.5	2060	155	73.9	153	---	433	80	4161	---	1810	1010	1/3	199	447	338
9	--	8.3	1.9	2160	242	104	243	---	409	150	5260	---	1650	1480	1/3	221	428	328
10	--	8.4	1.4	1940	160	67.6	127	---	323	83	4474	---	1300	708	1/3	204	382	304
11	25	8.2	6.3	763	126	18	7.4	1.4	910	645	5960	1250	342	46	1/3	244	206	200
12	22	-.--	---	850	66	7.7	2.3	2.1	636	1150	1520	43	420	53	1/3	206	226	214

Table 7: Geochemistry of subsurface waters, Sulphur Bank Mine. All measures are metric. BDL = below detectable limit. OOR = out of range. Sources are listed below.

1. Sulphur Bank Mine artificial geyser from a well about 1,500 ft deep on property of the Bradley Mining Co. Sampled October 4, 1966. From Berkstresser (1968, App. B, p. 38).

2. Sulphur Bank Mine well. From Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973 Tab. 2, pp. A10–A11).

3. Sulphur Bank Mine well. From Zimmerman (1975c, Tab. II).

4. Bradley Mining 1 flow test by Earth Energy, Inc., from Beall (1985).

5. Bradley Mining 2 well flow test by Earth Energy, Inc., from Beall (1985).

6. Borax Lake 7-1 well formation gas sampled April 11, 1978, 1,015 h by Phillips Petroleum Co., from Farrow (1983).

7. Borax Lake 7-1 well formation gas sampled April 12, 1978, 0820 h by Phillips Petroleum Co., from Farrow (1983) and Beall (1985).

8. Audrey A-1 well sampled February 10, 1983, 1,445 h by Phillips Petroleum Co., from Farrow (1983).

9. Audrey A-1 well sampled February 10, 1983, 1,455 h by Phillips Petroleum Co., from Farrow (1983).

10. Audrey A-1 well sampled February 10, 1983, 1,505 h by Phillips Petroleum Co., from Farrow (1983).

11. Audrey A-1 well baled sample by Phillips Petroleum Co., after Beall (1985).

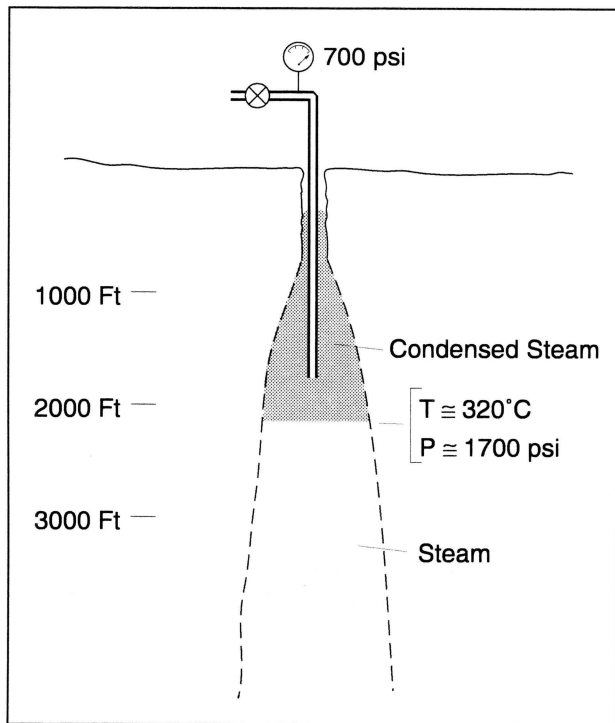12. Jorgensen 1 well flow test by Union Oil Co., after Beall (1985).

Figure 53: Diagram of phases in the Sulphur Bank hot spring. By R. Potter. From Burns, Potter, and Zyvoloski (1992, Fig. 9, p. 140).
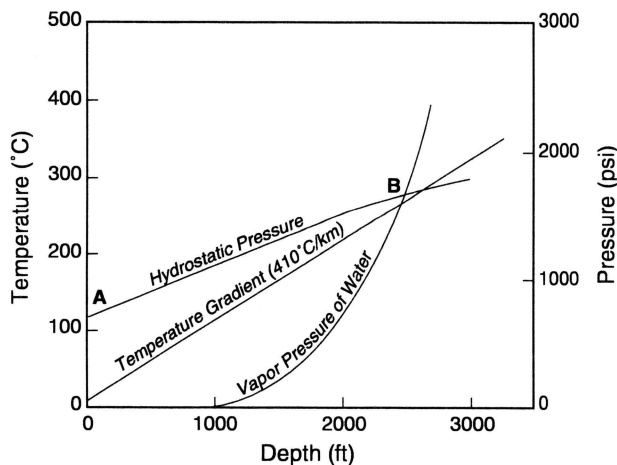

Figure 54: Pressure-temperature conditions in the Sulphur Bank hot spring. The gradient of 410°C/km was measured in the CL-1 well. By R. Potter. From Burns, Potter, and Zyvoloski (1992, Fig. 8, p. 139).

The physical conditions in two-phase hot springs were analyzed by Sheu, Torrance, and Turcotte (1979) for various flow rates. The column of two-phase fluid is delimited at the top by condensation and at the bottom by boiling. The condensation depth and the boiling depth vary with flow rate. At high flow rates, the two depths approach each other, and the two-phase column disappears. At low flow rates, the two-phase column lengthens.

We envisage the ascent of a packet of hot water at Sulphur Bank as follows. As the packet rises, the hydrostatic pressure drops, and when it drops about 50 bars, the boiling depth has been reached. Steam bubbles appear in the water column, and two-phase flow begins. The bubbles are a minor component, perhaps 10% by volume of the fluid. The ascending two-phase fluid loses heat to the wall rock, and eventually the condensation depth is reached at a pressure of about 10 bars. The steam bubbles disappear, and condensed hot water emerges at the surface.

A method of determining the length of a two-phase column under hydrostatic pressure is illustrated by Sheu, Torrance, and Turcotte (1979, Fig. 2, p. 7526). At Sulphur Bank Mine, the subsurface pressures encountered by well BM-1 show that pressures within it significantly exceed hydrostatic. The pressure is probably maintained by a near-surface choke in the pipe resulting from silica deposition. Faulting or increased rainfall could fracture this choke, release pressure, and conceivably could lead to phreatic eruptions (Fournier, 1983). Plumes of mercury in the soil (Beall, 1985, Fig. 4, p..397) and mercury-rich layers in the sediments of Oaks Arm (Figure 55) may be evidence of this. Figure 55 suggests that the last eruption took place 3,600 years ago and that the process has been continuing for 34,000 years. The recurrence rate is about one event every 5,000 years. This is not unreasonable for large events on faults in this area.
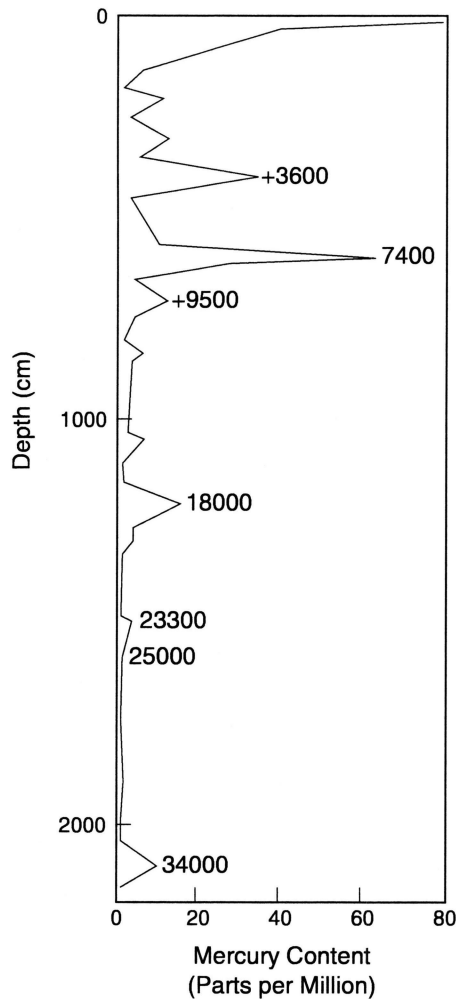
Figure 55: Mercury content in sediments of Oaks Arm. After Sims and White (1981, Fig. 117, p. 239).

Figure 56: Flow test of the Bradley Mining Company No. 1 well in May 1964. Compiled by R. Potter. From Burns and Potter (1993, Fig. 10, p. 321).
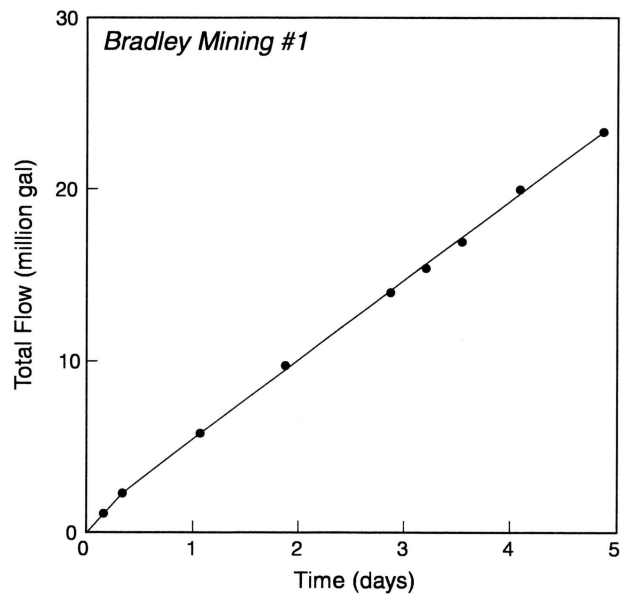
Figure 57: Cumulative flow from the Bradley Mining Company No. 1 well. Compiled by R. Potter. From Burns and Potter (1993, Fig. 11, p. 321).

Productive potential of the resource at Sulphur Bank Mine: The productive potential of Sulphur Bank hot spring is of major importance in development of a geothermal industry at Clearlake. Bradley Mining Company No.1 was flow-tested by Earth Energy, Inc., in May 1964. Beall (1985) says of the test ". . . it is clear that below 487.7 m (1,600 ft), a major producing interval was encountered." Figure 56 is a graph illustrating the flow test. At points A, C, and M to O, the well was shut in. At points B, D to L, and P to R, the well was flowing. R. M. Potter deduced the quadratic relationship $Q = 0.38\ SQRT(P)$ where Q is the flowrate in millions of gallons per day, and P is the pressure in psi. Using this relationship in Figure 56 gives the cumulative flow, shown in Figure 57.

From Figure 57 the productivity may be estimated at 135 MWt. Earth Energy, Inc., drilled a second well about 335.3 m (1,100 ft) away, BM-2, which was not a producer.

Koenig (1970) is quoted as saying that Magma Power Co. and Earth Energy, Inc., considered the field to be noncommercial largely because the high boron content created a severe problem of waste disposal (Zimmerman, 1975c, p. 12). Ten Dam is said to have reported in 1964 that three wells on the north side of the pit hit steam but reverted to water afterwards, but a well on the south side did not produce steam (Zimmerman, 1975c, p. 12).

However, these results were considered insufficient to preclude a steamfield at depth. To explore that possibility, Phillips Petroleum drilled the Borax Lake and Audrey wells. However, this two-well deep test failed to yield positive results, so the prospect was finally abandoned.

IX. DISCUSSION

A. Association of Thermal Waters with Faults

The isotope geochemistry shows a mixing trend between meteoric water and connate water, the latter dominating at Sulphur Bank and Wilbur Springs (White, Barnes, and O'Neil, 1973). Because of chemical and isotopic inhomogeneity, particularly boron/chloride ratios and tritium content, the waters do not originate from one large, liquid-dominated reservoir, but from separate, independent reservoirs (Goff, Adams, Trujillo, Counce, and Mansfield, 1993).

Lake County studied the hydrothermal potential of the county in 1983. The Phase I assessment was illustrated in Figure 14. The major fault systems in Lake County are the Collayomi Fault Zone and the Konocti Bay Fault Zone. Figure 58 shows hot spots, defined as places where estimated temperatures at 610 m (2,000 ft) below ground level are greater than 90°C. The compilers felt there is a definite correlation between hot spots and faulting. They said that except for one area between the fault zones, all the hot spots are associated with fault zones (Gennis, Blaydes, Niimi, and Fisher, 1984, pp. 21–22).

The U.S. Geological Survey studied the hydrothermal waters across a wide area. Figure 59 shows the nearly 100 sampling locations for analyses reported by Waring (1915), Berkstresser (1968), White, Muffler, and Truesdell (1971), Barnes, O'Neil, Rapp, and White (1973), Goff, Donnelly, Thompson, and Hearn (1977), and Thompson, Goff, and Donnelly (1978). Most of the samples were taken from springs. The figure suggests an association of springs with faults, especially in the northeast part of the map.
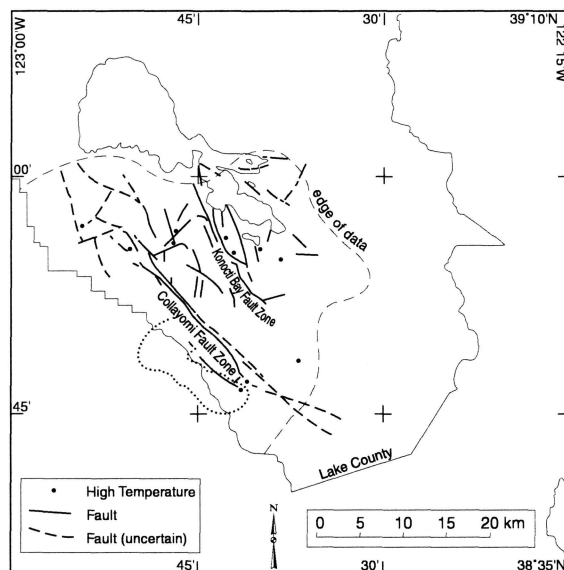
Figure 58: Hot spots in the Clear Lake volcanic field, showing association with faulting. Hot spots were determined as a temperature of 90°C or greater at a depth of 610 m (2,000 ft) below ground level, based on extrapolation of temperature gradients measured at the surface. From Gennis, Blaydes, Niimi, and Fisher (1984, Fig. 9, p. 23).

Figure 59: Springs in The Geysers–Clear Lake area, showing association with faulting. From Donnelly, Goff, and Nehring (1979, Fig. 1, p. 351). Peachtree Crossing Fault named from Manson (1989). Stony Creek Fault named from Barnes, Hinkle, Rapp, Heropoulos, and Vaughn (1973, Fig. 1, p. A3).

A compilation of structural and hydrothermal information for the region near the City of Clearlake is shown in Figure 60. This shows that all known hydrothermal waters, offshore gas leaks, and areas of hydrothermal alteration, occur on probable faults. It appears that all the known vents and resurgences might occur on a faults.

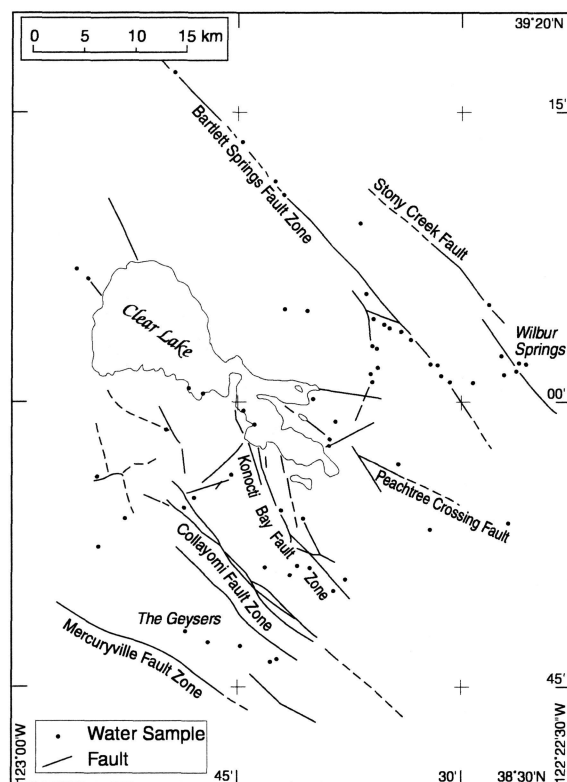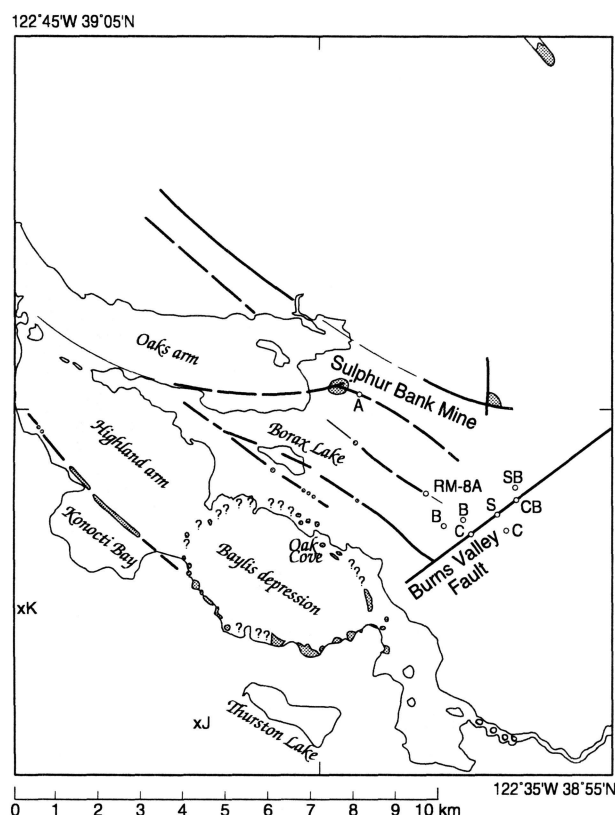*Figure 60: Geothermal manifestations of the Clearlake area, showing association with faulting. From Burns and Potter (1993, Fig. 6, p. 320). Offshore gaseous springs after Sims and Rymer (1976). Onshore areas of hydrothermal alteration after Manson (1989). Faults modified from Manson (1989). Deep wells are A = Audrey, K = Kettenhofen, J = Jorgensen. Geochemical high points are denoted B for boron, S for silica, and C for chlorine. RM-8A is a gradient well that ran down a fault zone. The question marks show the outline of a hypothetical subsidence basin named Baylis depression, from the small headland on the southern shore. Oak Cove hot spot occurs on the rim of this hypothetical depression.*

We conclude that for most of The Geysers–Clear Lake area outside The Geysers steamfield, fumeroles, hot springs, and areas of hydrothermal alteration, including mercury deposits, are controlled by faults. Faults provide the principal pathways for connate and metamorphic waters and magmatic gases to escape to the surface, and provide a reservoir for mixing of ascending with meteoric waters.

B. Exploration for Geothermal Resources

The most productive geothermal resource in northern California is the steamfield at The Geysers. The steamfield is a product of high-temperature gradients and a large reservoir. The Geysers–Clear Lake area is a region of high geothermal gradients, so the search for commercial geothermal resources was essentially a search for permeability.

Various exploration strategies in geology, geophysics, and geochemistry had mixed success.

The predominant host rock for The Geysers steamfield is Franciscan greywacke. No geological structure proved capable of predicting a repetition. "Serpentine structures," that is, blocks of greywacke cored by serpentine, were not helpful as guides to the occurrence of steam. There are probably no alpine-type piercement structures in the region. The "Knoxville model," of formations of permeable greywacke with a covering seal of impermeable sandstone and shale, was also not validated. The Maacama Antiform is possibly the structural cause of the permeability at The Geysers, but it is a unique geological structure without repetition in this geothermal area.

In petrology, serpentinization was not found to be an indicator of relevant hydrothermal activity. The plumbing was irrelevant to modern conditions. However, silica-carbonate rock, mercury mineralization, and hydrothermal alteration of rock (acid sulphate leaching) were indicators of conduits for thermal fluids that were in part still active. Hydrothermal

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alteration of soil and recent landslide debris is the best mineralogical guide to current fluid pathways.

In geophysics, potential-field geophysical methods did not give definite results, not particularly because of the inherent ambiguity of the methods and the complexity of the geology but probably because the studies reviewed here were applied at scales appropriate to wide-area surveys. High-resolution, ground-based surveys might provide useful additional information. The two most effective geophysical techniques were microseismic monitoring and electrical resistivity surveys.

Microseismic monitoring detected activity related to geothermal production at The Geysers (Burns, April 1996) and to faults in the vicinity of Clearlake. The prospecting observations near Clearlake were surprisingly successful, given the very limited recording time, which was less than a week.

Wide-area electrical resistivity surveys found a distinct low at Borax Lake. This had accompanying high heat flow but did not prove significant upon drilling. Detailed electrical surveys of Burns Valley found several low-resistivity zones in the underlying bedrock, but these did not prove to be significant either. Despite these negative results, the method offers promise in appropriate situations.

In geochemistry, the search was initially for "hydrothermal manifestations," or waters escaping from hidden steamfields (Facca and Tonani, 1967). The signatures of condensate waters were used at the Little Geysers and Castle Rock areas within the steamfield. However, the lack of steam condensates outside The Geysers steamfield meant that the search became one for hot-water systems in Franciscan rocks that could be developed as steamfields (Facca, 1973).

The stable-element geochemistry identified a methane-rich, high-chloride brine of the Central Valley, possibly of outliers of Great Valley Sequence rocks within the Coast Ranges and probably the Coastal Province of the Coast Ranges west from Skaggs Springs. The Central and Eastern Franciscan provinces of the Coast Ranges were recognized for ammonia, boron, and carbonate-rich thermal waters, with highly variable ratios of chemically conservative components such as boron to chloride.

Isotope geochemistry established the presence of three primary waters: meteoric water (from rainfall and snowmelt), connate water (high-chloride, methane-rich), metamorphic water (low-chloride, high-boron, ammonia-rich). Thermal waters throughout the Central and Eastern provinces of the Coast Range were shown to be mixtures of the connate or metamorphic waters with meteoric water. The carbon dioxide may be derived from magmatic gases.

One model, of a widespread hydrothermal source leaking out boron-ammonia-carbon-dioxide vapor, was disproven. The high variability in boron/chloride ratios and tritium content indicated that each hot spring was a separate, distinct circulation system.

A set of favorable indicators for steamfield exploration was thermal springs at the boiling point, mercury mineralization, abundant hydrothermal alteration, and high geothermal gradients. The most practical exploration technique was to drill patterns of shallow "geothermal gradient" wells in an indicated area, followed by deep exploration wells.

However, deep drilling and testing on lines through the Clear Lake volcanic field and from Borax Lake to Chalk Mountain (see "volcanic alignments" in Figure 6) failed to yield an exploitable resource. The wells, when tested at depths ranging from 1,500 m (5,000 ft) to

3 000 m (10,000 ft) would flow strongly for periods of hours to days, with the pressurized water flashing to steam in the bore, but would yield unproductive flow rates or fade.

This failure to find exploitable deep hot-water resources does not mean that they do not exist. Wright (1991) considered that the region had not been properly tested, and considered that The Geysers "Megadistrict" might be capable of an additional 500 MWe of hydrothermal development in addition to that already being produced at The Geysers steamfield.

Conversely, however, the exploration results demonstrate that much of the hydrothermal activity is confined to conduits, between which are large volumes of impermeable hot rock. These may be suitable for HDR or other advanced geothermal production techniques.

C. Geothermal Regimes

Introduction: The Clear Lake geothermal resource may be divided into a conductive, steamfield, hot spring, and hot-water aquifer regimes.

The results of exploration were the establishment of four geothermal regimes, which differ from each other in the geometry of the permeability and the geochemistry of the associated waters.

These are

(1) a conductive regime,

(2) the steamfield at The Geysers,

(3) one hundred or so fault-controlled hot springs, and

(4) hot-water aquifers in shallow sedimentary basins at Big Valley and Burns Valley.

Conductive regime: It is shown in a companion report (Burns, August 1996) that the previous volcanic model, of a vat-like magma chamber cooling by lateral heat flow, as from a cooling vertical cylinder, cannot be substantiated. Instead, the source of heat is a two-level magmatic complex. A better model of the deepseated basaltic source is a thin layer or plate with heat flux vectors pointing vertically, normal to the plate. The result is that isotherms are not vertical concentric cylinders but plane horizontal sheets.

The conductive regime is a thick slab of Franciscan rock which comes to the surface at The Geysers and at Clearlake, but is downfaulted and buried under Clear Lake Volcanics in the intervening country. This is the "large HDR prospect" of Goff and Decker (1982, 1983). The slab is sufficiently thick and homogeneous that the isotherms are smooth, near-horizontal, level, surfaces in subsurface profiles along the magmatic axis (SW-NE direction). There are insufficient deep wells to establish the form of the isotherms in the transverse (NW-SE) direction, but it appears that they turn down and dip quite steeply in the region near the 4-hfu boundary of Walters and Coombs (1989, 1992).

The conductive fluxplate at depth is widespread and very hot. Because it is so impermeable, fluids are constrained to permeable zones near faults, or in overlying permeable strata. Accordingly, we find numerous, small, self-contained, hydrothermal circulation systems— virtually one for each isolated zone of permeability. These fall into two major types, convective flow in faults with hot springs at the surface, or advection in permeable blankets leading to hot-water aquifers. If the local geothermal gradient is low, the regimes are single-phase hydrothermal. In two places, at The Geysers and at Sulphur Bank Mine, the gradient is sufficiently high to generate two-phase flow, vapor-dominated and water-dominated, respectively.

Steamfield regime: At the southwest end of the heat-flow axis is the steamfield at The Geysers, the largest of its type in the world. Dry steam occupies fractures in Franciscan graywacke in the arch of an antiform. One widely expressed view is that the "doming" is related to intrusion, for example, Nielson, Walters, and Hulen (1991). However, it is shown in a companion report that the antiform is of San Andrean affinities, that is, related to the current faulting and stress regime, and is probably younger than 0.1 ma. Rather than "extension related to doming" the concentric fractures are more likely to be integral to the antiform. The dilitational event that created the steamfield is probably part of the same current deformational process.

The steamfield probably began life as a hot-water system. Deformation accompanying growth of the antiform eventually led to rupturing, which in turn led to vaporization (Pruess, 1985). The current regime is a vapor-dominant heat pipe. Older models required the reservoir to be a chamber sealed behind geological impervious barriers or plugged by chemical deposition, but new models have proposed physical mechanisms of containment somewhat analogous to hydrodynamic traps (Pruess, 1985).

Hot spring regimes: The geothermal gradient along the heat-flow axis is generally about 90 mK/m. The plate is intersected by faults, which provide pathways to depth. Meteoric water can penetrate fractures to very considerable depths, pick up heat at depth, and return to the surface driven by buoyancy.

Each hot spring is largely independent. Meteoric waters percolate into fault zones, react with wall rocks, are heated, then return to the surface under thermal buoyancy drive.

The hot spring on the Burns Valley Fault in the upper part of the valley was found by contouring residential water wells for trace amounts of boron, chlorine, and silica. The water does not reach the surface but leaks away in the permeable Pliocene sediments that fill Burns Valley.

The hot spring at Sulphur Bank Mine is structurally controlled, being a thread in one fault or a pipe at the intersection of two faults. The study of Burns, Potter, and Zyvoloski (1992) identified the system as two-phase, and it may be termed a liquid-dominated heat pipe.

Hot-water aquifers: We have noted shallow geothermal aquifers SW of Highlands Arm at Ag Park and Big Valley. These are formed of fluids circulating in a surface blanket of permeable rock and acquiring heat by conduction from beneath. There is conductive heatflow upwards through the rock matrix, which is acquired by meteoric water infiltrating downward through the pore spaces. When the water resurges at a fault zone, the resurgence is warmed by the acquired heat.

Stone (1987) and Burns, Potter, and Zyvoloski (1992) discussed the notion that Burns Valley acquired hot fluids by inflow from the sides. However, the system discovered by trace element surveys in the upper valley (see Figure 45) is fed by a deep source. Hot waters do not emerge at the surface but come up under gravels and flow away as a subsurface plume, as at Wairakei in New Zealand.

Stone (1987) thought the hot water discovered by thermistor and radon surveys lower in the valley (see Figure 33) was due to water rising in a fracture and emerging under the gravels. The Leisek wells were targeted to intersect that source. This could be the same fracture; however, the relationship of the hot waters in the upper valley to those in the lower valley is obscure.

D. Conclusions

The Geysers–Clear Lake geothermal area is occupied by The Geysers steamfield at its center. The annular region surrounding the steamfield is occupied by a wide, extensive, conductive region, punctuated by numerous, independent, fault-controlled hydrothermal systems. Hot-water aquifers in shallow sedimentary basins have been used for agricultural purposes, as at Ag Park. However, none of the systems have proven capable of sustaining commercially viable electric power production.

Extraction of the unused geothermal heat will require advanced geothermal engineering. There is probably insufficient space to build advanced systems in impermeable rock free of interference with natural hydraulic systems, so it will be necessary to study, understand, and either avoid or use, some of the existing hydrothermal systems. At present, we have only the mechanical or hydraulic data necessary to say that the selection of a suitable advanced production technology is site dependent. There is an opportunity and need for HDR, hot wet rock, and other advanced geothermal technologies in the future development of this resource.

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LOCAL RECORD OFFICES AND ARCHIVES

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