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Geothermal Steam in The Geysers–Clear Lake Region, California

ABSTRACT

Dry, superheated natural steam is produced for the generation of electrical power from wells in the Mayacmas Mountains, north-central California Coast Ranges. The indicated source of the heat is a shallow intrusive magma body emplaced in Quaternary to Holocene time. Magmatic heat is transmitted through the largely impermeable country rock by conduction. Convectional heating takes place in stream reservoirs, predominantly zones of permeability and porosity caused by faulting and shearing. The thermal fluid is derived from meteoric water, but some portion is probably derived from the magma. It is, at least in the exploited part of the system, in the vapor state. This controls the temperature and pressure regime, and reservoir pressures are lower than hydrostatic for similar depths in a liquid-dominated system. Generation capability was 182,000 kwh in 1971, and a capability of more than 600,000 kwh is projected for 1975.

INTRODUCTION

Electrical power is generated from dry, superheated geothermal steam obtained from wells in the Mayacmas Mountains of the Clear Lake region, California Coast Ranges, about 90 mi north of San Francisco (Fig. 1).

HISTORY OF GEOTHERMAL STEAM PRODUCTION

J. D. Grant of Healdsburg began drilling a well in 1921 at The Geysers fumarole tract on Big Sulphur Creek, Sonoma County, to obtain natural steam for electrical generation.

His well blew out with steam at a shallow depth when closed-in, and was abandoned. The next year the well, known as no. 1, was drilled to 203 ft, and completed as a steam well with 8-in. casing to a depth of 80 ft. The initial static pressure was 64 lb. A second well was begun later that year within 50 ft of well no. 1. This was drilled to 318 ft and completed with 67 lb initial static pressure. A third well was drilled in 1924 but was abandoned at 154 ft. During these early years, The Geysers Development Company was organized to develop the encouraging natural steam properties. In 1925, the company drilled five steam wells, which were completed with varying steam capacities. The steam was superheated by 15° C to 25° C. The maximum temperature recorded was 190° C in well no. 5, which also had the highest shut-in pressure of 167.5 psig.

The combined capability of wells 4, 5, 6, and 7 was 137,500 lb of steam per hour, which was estimated to represent a generating capacity of 4,500 kwh. Well no. 5 was the largest producer with 52,000 lb/hr. As there was at the time no market for the energy, the project was suspended. The wells were abandoned in 1969 by the present operator.

In 1955, Magma Power Co. obtained a 99-yr lease on The Geysers Development Co. prop-

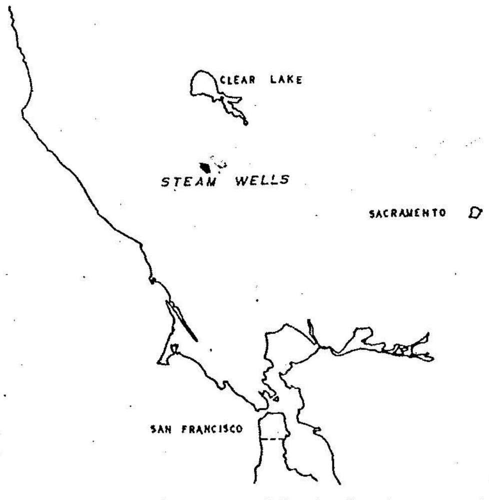

Figure 1. Northwestern California, showing general area of steam wells in Clear Lake region.

Geological Society of America Bulletin, v. 83, p. 1449–1468. 15 figs., May 1972

erties, which included other lands and hot springs localities. Magma Power Co. formed a joint venture with Thermal Power Co. and from 1957 through 1966 drilled a total of 42 geothermal wells at The Geysers, Sulphur Bank, and the Little Geysers.

The steam-producing capabilities of the 42 wells ranged from an insignificant amount (Sulphur Banks no. 1 original hole) to as much as 312,000 lb/hr (Happy Jack no. 1). Few data are officially released about the wells, but by assigning a capability of 150,000 lb per hour to the unknown steam flows, the wells have a raw capability of about 4.7 million lb of steam per hour. At the conversion rate in current practice of 18.53 lb/kwh, this represents 253,600 kwh.

In the summer of 1966, Union Oil Co. drilled the Ottoboni no. 1 well in an area north of the Magma-Thermal development. The well was completed for 167,000 lb/hr. Magma-Thermal and Union later agreed to pool their leases and to jointly develop the prospective and productive acreage of both, with Union being desig-

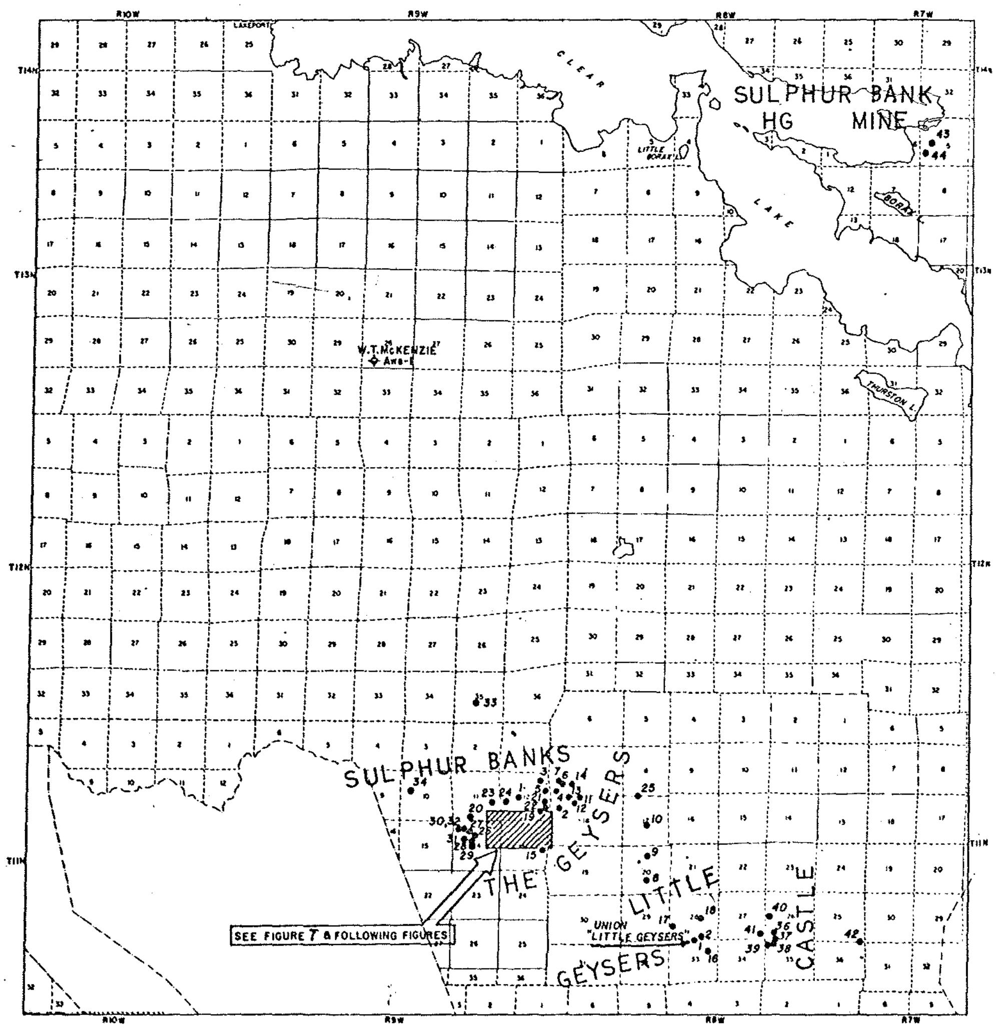

Figure 2. Location of steam tests and producing areas in the Clear Lake area.

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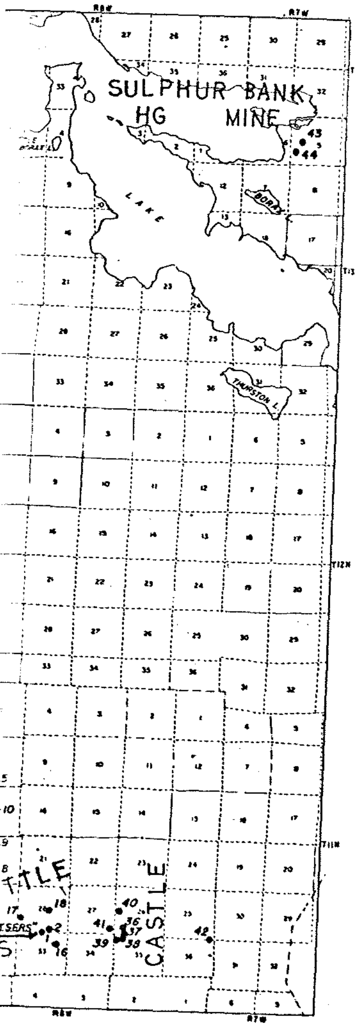

the Clear Lake area.

nated operator. These leased properties lie in townships 10 N., 7 W. to 10 W.; 11 N., 7 W. to 10 W.; and 12 N., 8 W. to 10 W.

Union and Magma-Thermal individually or jointly had drilled 70 steam wells by January 1971. In addition, several older wells were deepened with an increase in productivity, and some wells were abandoned. Included in the 70 wells is the uncontrolled Geysers no. 4 steam blowout.

In 1967, Geothermal Resources International began drilling on its leased property west of the Sulphur Bank area. Of seven wells drilled through 1969, three were completed with announced equivalents of 10,000 kwh or higher.

In 1967 and 1968, Signal Oil and Gas Co. drilled three wildcat tests, completing one and abandoning two. In 1969, this operator discovered the Castle field in Lake County. As of January 1, 1971, six steam wells had been completed with an estimated capability of 540,000 lb of steam per hour, equivalent to 29,142 kwh.

Again, assigning 150,000 lb of steam per hour to the unknown flows, all the wells producing and those not yet hooked up through 1970 have a raw capability of more than 8.5 million lb/hr, which would generate more than 458,716 kwh (Fig. 2).

Data on the steam wells are summarized in Table A[1], which includes information on wells drilled outside the presently producing areas (Sulphur Bank mercury mine and Wilbur Hot Springs).

One test was drilled for oil and gas in this region, the McKenzie, Evelyn Awe no. 1 (SW28 13N–9W). This was drilled and abandoned at 1,679 ft in 1949.

Pacific Gas and Electric Co. purchases the steam for electrical generation on site. The first plant was installed at The Geysers in 1960 with a capacity of 12,000 kwh. With the addition of a second plant, this capacity was increased to 26,000 kwh. Units 3 and 4 generate 56,000 kwh from Sulphur Banks. Units 5 and 6 are scheduled for operation in 1971 and will produce 100,000 kwh. Future increments of generating capability are planned through 1975. Plants will normally be built when a local area can demonstrate a steam capability equivalent to 100,000 kwh.

CLEAR LAKE GEOTHERMAL AREA

Crustal Relations

The Clear Lake geothermal area is defined as including the present site of steam production and potential areas in the Mayacmas Mountains, the miogeosynclinal area to the east, and the Quaternary volcanic field.

On a regional scale, the Clear Lake geothermal area is on the northwestern extension of the Diablo antiform described by Bailey and others (1964), an arch in the Mesozoic Franciscan rocks of western California, extending nearly 350 mi from Parkfield at the southeast to a point northwest of Clear Lake. About 35 mi southeast of Clear Lake, there are extensive Pliocene volcanic rocks in the Mt. St. Helena and Sonoma Mountain areas. At Clear Lake, the volcanic field is no older than Pleistocene (Brice, 1953).

The eugeosynclinal, ocean-floor Franciscan rocks are, in part, contemporaneous with the shelf-and-slope Great Valley miogeosynclinal rocks. The Great Valley sequence overlies the Franciscan rocks along thrust faults, throughout the length of the Great Valley of California. This overthrust appears to represent a Benioff seismic zone (Hamilton, 1969).

Stratigraphy

General. The Mesozoic Franciscan and Great Valley rocks and the Quaternary Clear Lake volcanic series are the most widespread rocks in the area (Fig. 3).

The oldest Tertiary strata are the "Tejon" (Eocene) and "Martinez" (Paleocene), separated by an unconformity. The combined thickness exceeds 5,000 ft of marine sandstone and mudstone. They crop out to the east of the Mayacmas Mountains and are separated from beds above and below by unconformities (Brice, 1953).

The lacustrine beds of the Pliocene-Pleistocene Cache Formation unconformably overlie Mesozoic and Tertiary beds. Up to 2,000 ft of Pliocene sediments, assigned to the Merced Formation, unconformably overlie the Franciscan rocks in the southwest part of the Mayacmas Mountains (McNitt, 1968).

Franciscan Assemblage. The Franciscan Assemblage is divided by McNitt (1968) in

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[1] Tables A and B (NAPS no. 01729) may be obtained by writing to CCM Information Corp.—NAPS, 909 Third Ave., New York, New York 10023, enclosing $5 for photocopies or $2 for microfiche. Make checks payable to NAPS.

the Mayacmas Mountains into an upper unit, 10,000 ft thick, composed of interbedded shale and graywacke; and a lower unit, 15,000 ft, composed of diverse rock types, the most common being graywacke. Basalt is the next most abundant rock type of the lower unit, with an aggregate thickness of 7,000 ft (McNitt, 1968). The basalt commonly lies at the top of the lower unit. Other rock types in the lower unit include serpentinite, chert, schist, and diabase.

The Franciscan Assemblage ranges in age from Late Jurassic Tithonian to Late Cretaceous Turonian stages (Swe and Dickinson, 1970). It is a eugeosynclinal suite.

Great Valley Sequence. The Great Valley sequence consists of more than 35,000 ft of clastic marine sedimentary rocks, ranging in age from Late Jurassic Tithonian to Late Cretaceous Campanian (Swe and Dickinson, 1970). Broadly, the Great Valley sequence is a miogeosynclinal suite of mudstone, sandstone, and conglomerate.

Clear Lake Volcanic Series. The volcanic rocks are expressed in the large landforms, roughly north to south, of Mt. Konocti, Mt. Hannah, Seigler Mountain, Roundtop Mountain, Perini Hill, Boggs Mountain, and Cobb Mountain. They are flows and pyroclastic rocks which lie primarily upon the Great Valley sequence or the Franciscan Assemblage east of the Mayacmas Mountains.

Rock types include dacitic flows (Mt. Konocti), dacitic and andesitic flows (Mt. Hannah and Seigler Mountain), andesite (Boggs Mountain), rhyolite and rhyolite tuff (Cobb Mountain), obsidian (tract between Mt. Konocti and Seigler Mountain), and minor exposures of rhyolite (Caldwell Pines and Tyler Valley).

The volume of the exposed volcanic materials is estimated by Brice (1953) at 5.75 cu mi of which dacite is the most common.

Volcanism first occurred in the early Pleistocene, as evidenced by tuff and basalt that are intercalated in the uppermost Cache Formation (Brice, 1953). Koenig (1969) cites apparently unpublished radiometric ages of from 3,000,000 to 50,000 yrs old. The sharp, unweathered topography of many of these volcanic landforms and the freshness of exposed material in many areas also testify to the geologically recent age of the series. From the relative degree of erosion, Mt. Hannah appears to be younger than Mt. Konocti or Cobb Mountain (Brice, 1953).

Structure

The Clear Lake geothermal area consists of the following structural elements: the Franciscan terrane of the Mayacmas Mountains; the Great Valley sequence klippe; the Quaternary volcanic pile, and its source, the postulated near-surface magma chamber; and the alluvial Big Valley.

Franciscan Terrane. The Mayacmas Mountains, made up mostly of Franciscan rocks, are broadly homoclinal in structure, complexly faulted, and dip northeastward. According to McNitt (1968), stratigraphically lower and older Franciscan is progressively exposed from the southwest to the northeast (Fig. 3). Faults trend northwest, parallel or subparallel to the regional grain, and many are curved. Figure 3 is based on McNitt (1968), Swe and Dickinson (1970), and the author's interpretation of aerial photogeology of faults at the northeast belt of the Mayacmas Mountains.

The faults seem to be concentrically organized about 5 mi west and southwest of Mt. Hannah into a system of gently imbricate or intersecting and more concentric fractures, generally concave toward the northeast. This curving loses definition with increasing distance to the southwest. The upthrown side of faults are generally on the northeast. These faults are regarded by the writer to be predominantly reverse, although McNitt (1968) portrays them as predominantly normal.

The preservation of the Merced Formation in a graben in townships 11 N., 9 W., and 11 N., 10 W. (Fig. 3) suggests that the maximum age of faulting is late Pliocene (McNitt, 1968). If the minor outcrops of Clear Lake volcanic rocks at Caldwell Pines and Tyler Valley are erosional remnants, then the exposures, initially more extensive, were the object of erosion that was aggravated by uplift of the Mayacmas Mountains. The Quaternary alluvium at Tyler Valley (and elsewhere) is a remnant of an older drainage system that has been disrupted by very young faulting and uplift. Quaternary terrace deposits on the east side of Big Valley and southwest of Kelseyville contain much obsidian debris, which is certainly derived from the obsidian deposits near Mt. Konocti. The Cache Formation near Kelseyville has been tilted and

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Brice, 1953).

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faulted. Lastly, seismicity testifies to continuing tectonic activity.

Topographically, there is a rough progression in elevation across the Mayacmas Mountains from southwest to northeast. This is concordant with the progressive uplift in that direction.

In summary, the Mayacmas Mountains have been tectonically active from Pliocene through very late Pleistocene time, and probably into the Holocene. Plutonism is likely to have abetted this uplift. The youngest pulses of uplift occurred in the northeastern belt.

Great Valley Klippe. The Great Valley sequence is a complexly faulted mass in thrust contact with the Franciscan terrane. The sole thrust of a number of thrusts is the Soda Creek fault of Swe and Dickinson (1970).

Tectonic Relations between Franciscan and Great Valley units. The Soda Creek thrust fault, which separates Franciscan from Great Valley units is presumed to be the upper edge of a fossil Benioff zone. It is masked by volcanic rocks at Boggs Mountain but cuts across the Quaternary obsidian of Camel Back Ridge. From its effect on these volcanic rocks, movement on this fault must have persisted into the Quaternary at least.

Quaternary Volcanic Pile and the Magma Chamber. The Clear Lake volcanic series was apparently extruded from a system of northwest-trending fissures; Cobb Mountain is a localized vent for the more explosive phase of rhyolite (Brice, 1953).

The Clear Lake geothermal area is the locus of a nearly circular Bouguer gravity anomaly of nearly 200 sq mi (R. Chapman, 1965, personal commun.; Mineral Information Service, 1966). The center of this feature is a minimum of more than −50 mgals, precisely underlying Mt. Hannah. Studies by Moore (1962) show a direct, causal relation between Bouguer gravity response and Cenozoic volcanic rocks based on Niggli k-values. These values are high for the Clear Lake volcanic rocks. Where k-values are high, the Bouguer gravity response is a low. Moore (1962) concludes that the connection is more related to the geographic location of an igneous body than to its age or mode of emplacement.

The arcuate fault pattern about Mt. Hannah and the Bouguer gravity contours show correspondence. This is interpreted as a reflection of the volcano-tectonic uplift. Here is a parallel to the Italian steam-producing areas of Larderello and Monte Amiata, where there is agreement between Bouguer gravity contours of minima; curved, concentric fractures; and uplift (Marchesini and others, 1962).

The source of the volcanic products at Clear Lake is presumed to be a relatively shallow magma body. Its agressive emplacement would have arched and uplifted the sedimentary roof, allowing the extrusion of the Clear Lake volcanic rocks along fissures and vents. The resultant structure is volcano-tectonic in nature.

Seismicity

The Clear Lake region is seismically active. Epicenters of minor and medium shocks have been in the Mayacmas Mountains, near Kelseyville, and in the Lakeport area on the west shore of Clear Lake. Historically the strongest tremor in the region was the June 6, 1962 earthquake with an epicenter approximately 10 mi northwest of Kelseyville, at a modified Mercalli intensity of VII.

HOT SPRINGS

The principal hot springs of the Clear Lake geothermal area are summarized on Table B, and locations are shown on Figure 4.

These thermal and mineralized waters may be compared to examples of regional ground water at Alexander and Cloverdale valleys to the west of the Mayacmas Mountains (Table 1).

Certain of the hot springs have geochemical indicators or parameters by which a geothermal potential might be identified.

1. **Calcium.** Calcium is the principal cation in fresh natural waters (Hem, 1970). In waters with a suspected magmatic contribution, the solubility of calcite decreases with increasing temperature, to solubilities controlled largely by salinity and pH (White, 1970).

2. **Chloride.** Chlorides are typically in low concentrations in acid-sulfate type waters in a volcanic environment. White (1970) remarks that no liquid water associated with a vapor-dominated stream reservoir is known to have a Cl concentration in excess of about 15 ppm, and conversely, a chloride water body with more than 50 ppm is suggestive of a hot-water system. The Geysers and Castle hot springs, both surface waters of a vapor-dominated system, have low Cl contents. Cl may be in relatively high concentrations in acid-sulfate-chloride waters of volcanic environments (White and

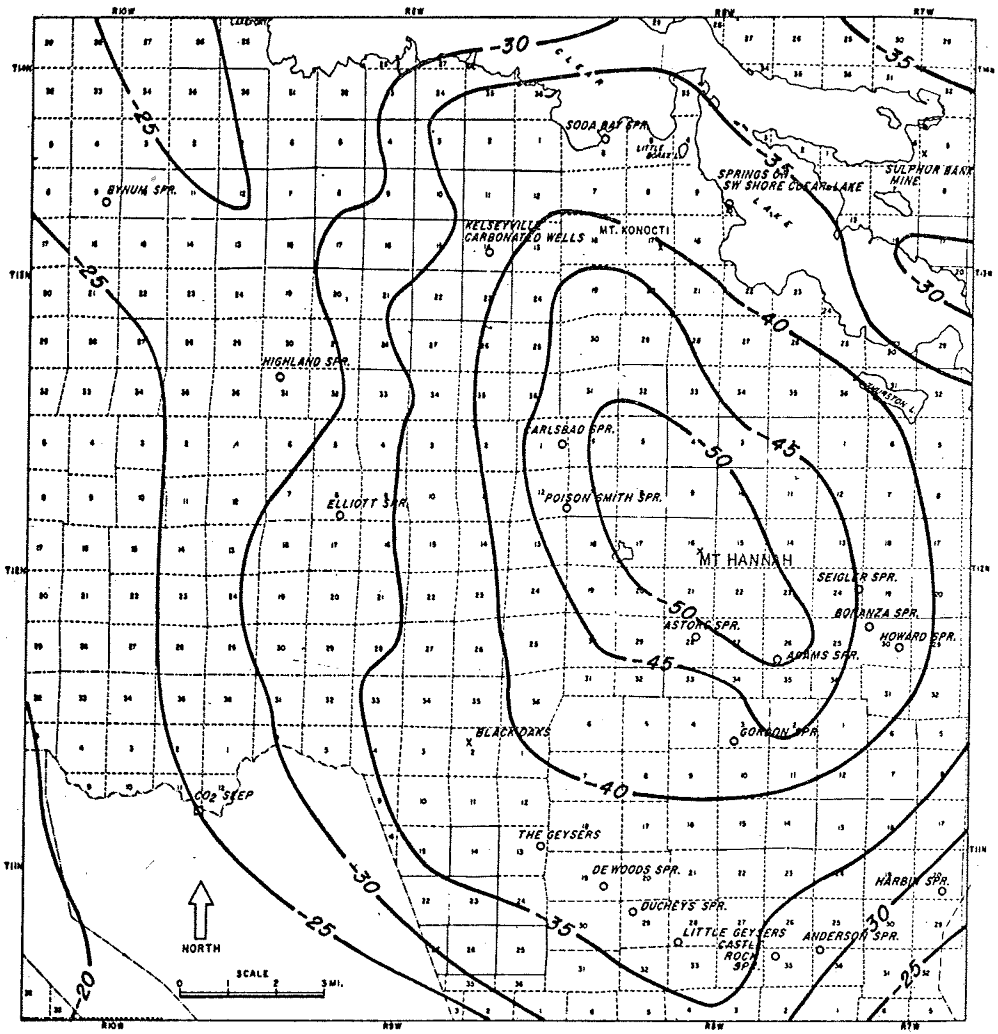

Figure 4. Regional Bouguer gravity contours, after Mineral Information Service (1966), and location of hot springs.

others, 1963), although sulfate is the dominant anion.

3. **Lithium.** Relative contents of Li and the Li/Na ratio may reflect lithium from volcanic emanations (White and others, 1963). Relatively high Li/Na ratios may suggest volcanic emanations in the water.

4. **Magnesium.** Low Mg contents are characteristic of a high temperature system (White, 1970). It is generally present in low amounts in waters of volcanic environments (White and others, 1963). Low Mg/Ca ratios are similarly characteristic of a high temperature hydrothermal system (White, 1970). High concentrations can be derived from reaction of water with magnesium silicate minerals, as at Seigler Springs (Hem, 1970).

At high temperatures, Mg favors a solid phase such as montmorillonite (White, 1970). Bailey and others (1964) have described Franciscan graywacke near The Geysers largely as being hydrothermally altered to a montmorillonite-rich rock.

5. **Silica.** SiO_2 is normally present in high concentrations in thermal waters with a suspected magmatic contribution. Fournier and

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TABLE 1. GROUND WATE

Chemical constituent or property
Ca
Mg
Na
HCO_3
Cl
B
total solids
PH
temperature

Source: (Cardwell

*SiO2, apparently

Rowe (1966) re
subsurface temp
dissolved SiO_2 a
face spring or
Fournier and
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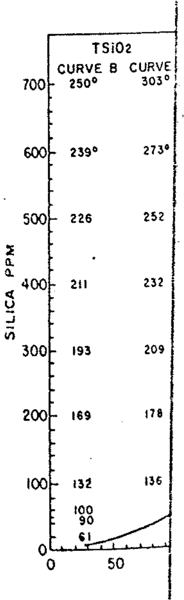

Figure 5. Sili
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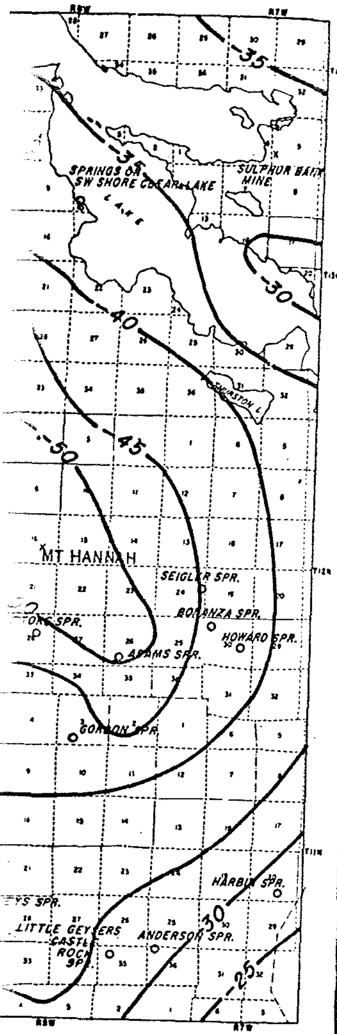

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ABLE 1. GROUND WATER IN ALEXANDER AND CLOVERDALE VALLEYS*

hemical constituent or property	Concentration in parts per million or measurement of the property
Ca	.5 to 60
Mg	11 to 275
Na	15 to 143
HCO_3	202, 300, 680
Cl	8.5 to 9.3 in 4 samples, 555 in one
B	zero to 40
total solids	510 and 2,650
PH	7.1 and 7.3
temperature	14°C and 18°C

Source: (Cardwell, 1965).

**SiO2, apparently absent.*

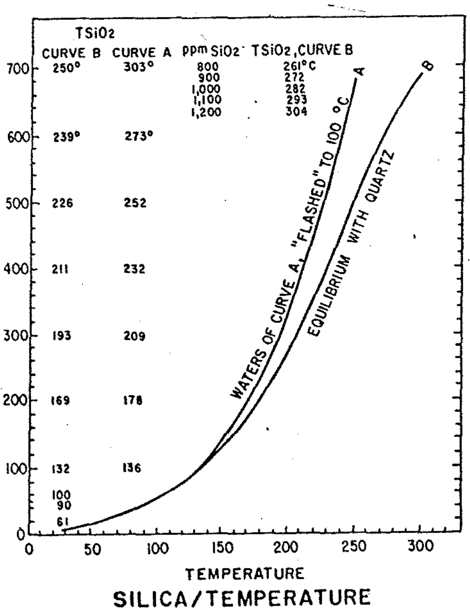
Rowe (1966) refined a concept for estimating subsurface temperature from the amount of dissolved SiO_2 and the temperature of the surface spring or flow. White (1970) modified Fournier and Rowe, and his temperature estimation chart is included as Figure 5A.

6. **Sodium.** Figure 5B shows experimental and empirical curves for atomic Na/K ratios, derived by White (1970). Curve "G" is proposed for general use in estimating subsurface temperatures of a hydrothermal system. The atomic Na/K ratio has proved about as reliable as SiO_2 contents for predicting temperatures from deep-well samples above 200° C (White, 1970).

7. **Total Solids.** Thermal and mineralized waters associated with volcanism or epithermal mineral deposits should be expected to have generally more dissolved solids than natural ground waters from the same region.

8. **Temperature.** Abnormally high temperature of surface springs in a volcanic environment is usually the first indicator of a hydrothermal system. Temperatures of waters related to epithermal mineral deposits may also be high, for example Sulphur Bank mercury mine and Wilbur Springs.

9. **Other Qualities.** Cold CO_2 seeps are located in sections 11 and 12, T. 11 N., R. 10 W. This is the principal noncondensable gas at



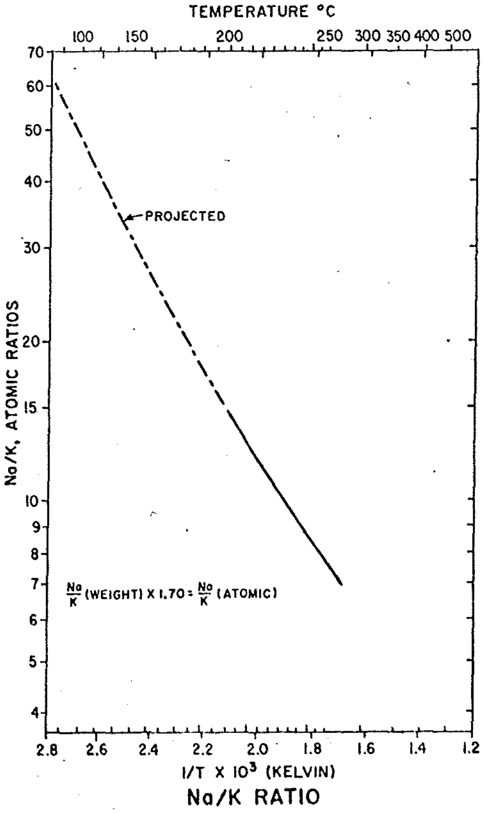


Figure 5. Silica/temperature and atomic Na/K charts for estimation of underground temperature after White (1970). White's curve "G" is shown in the atomic Na/K chart, which is recommended for general use.

The Geysers steam production. Seeps of CH_4 are known from the Clear Lake geothermal area (Thurston Lake and Kelseyville). The Sulphur Bank no. 4 steam well was originally drilled to 1,680 ft and suspended as a cool noncommercial well; it was, however, capable of flowing measurable amounts of CH_4 at 125 lb shut-in pressure. Radioactivity was first noted at The Geysers steam well flows in the 1920s (Bradley, 1922).

The Geysers and Castle are the two groups of hot springs known to be related to a vapor-dominated geothermal system in the Clear Lake geothermal area. They are characterized by (1) high temperatures, (2) high concentrations of silica, (3) low concentrations of chloride, and (4) high concentrations of sulfate. Other geochemical and physical parameters may be quite variable. A detailed, comparative study of all geochemical and physical parameters is an essential tool in the exploration and development of geothermal resources.

STEAM PRODUCTION

Nature

As far as investigated, the Mayacmas Mountains steam production is of the vapor-dominated type system, recently described by White and others (1971). It is thereby characterized by the produced steam being dry and superheated, and existing at rather uniform temperatures and pressures lower than hydrostatic for similar depths in a liquid-dominated system.

The vapor within the system is derived from boil-off from a deep water table. This deep water table must lie at depths greater than 9,000 ft, that is, beyond the penetration of the deepest wells to date. Within the vapor range, temperature and pressure behavior is basically that of a continuous steam phase. The most probable temperature and pressure range for a vapor-dominated system is 236° C to 240° C and 32 kg/cm^2 to 34 kg/cm^2 (455 to 483 psi). Temperatures and pressures may exceed these limits because of the effect of dissolved solids and the pressures of other gases (Fig. 6).

The produced steam is derived from local pore-space water in the vapor-dominated reservior above the deep water table. Liquid water and vapor coexist in these rocks. The rocks are gravity drained as steam and other gases rise in the largest channels and condense at the reservoir borders. This condensate percolates down into the reservoir, attracted to the narrow channels and pore spaces because of surface tension and the lower specific resistance of the liquid flow in relation to that of vapor (White and others, 1971).

The reservoir water body and its boiled off vapor are primarily meteoric in origin. The hydrothermal system is replenished by the recharge of meteoric waters. With a sufficiently potent heat source, or a decreasing recharge rate, the boil-off will exceed recharge. At this point, an initially hot-water system becomes vapor dominated. Heat from the presumed magmatic source is transferred by conduction through the Franciscan country rock which has slight to nil permeability. The steam reservoirs are primarily shear zones, related to faulting. Within these zones, with amplified permeability and porosity, convectional heating, with its lower thermal gradient and equalizing effect, prevails[2].

Superheat is due to the fact that the deep-water body is a brine and is superheated in respect to pure water at the same pressure. Steam boiled from a 25 percent NaCl brine at 35 kg/cm^2 is superheated by 12° C (White and others, 1971). Superheat also occurs with decompression. Most of the heat content of the reservoir is stored in the solid state (White, 1970). The shear zones within the hydrothermal system are presumedly the avenues for recharge, as well.

The steam reservoirs are isolated laterally and from above and below by cooler regions which are effectively impermeable. This can be due to innate impermeability of the rock, or deposition of minerals which seal the reservoir. Silica may be deposited by hot waters at the reservoir boundary as they flow into cooler regions. Conversely, cool waters may deposit $CaCO_3$ and $CaSO_4$ as they flow into heated regions.

At the borders of the reservoir, wells may encounter liquid water that may be accompanied by steam. This liquid is derived from

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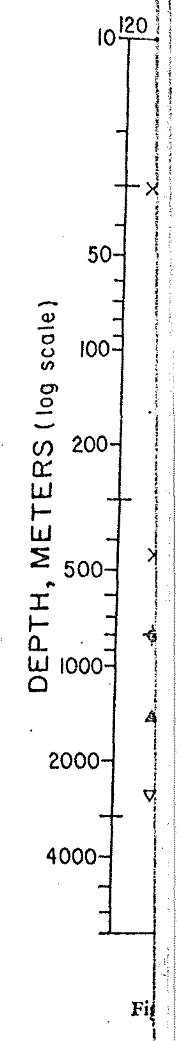
[2] The Franciscan "sandstones" (graywackes) are estimated (Decius, 1961) to have permeability less than 1 millidarcy and porosity less than 10 percent. These figures are probably high, except for shear zones or localized stringers. Grindley (1965) states that parts of the Wairakei reservoir with permeabilities of 1 millidarcy are nonproductive. Wells drawing on Wairakei acquifer storage (that is, innate permeability) have permeabilities of from 5 to 30 millidarcies; wells drawing on fault reservoirs have permeabilities on the order of 1 darcy and higher.



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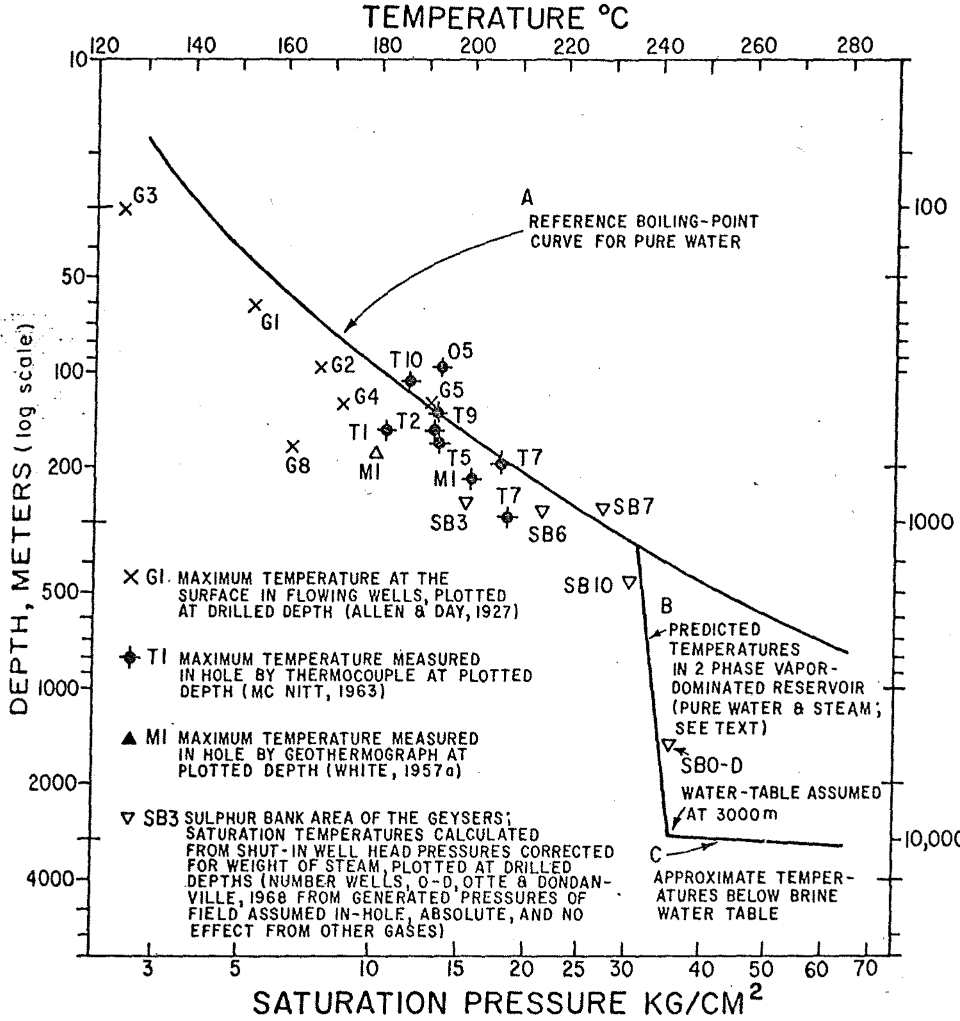


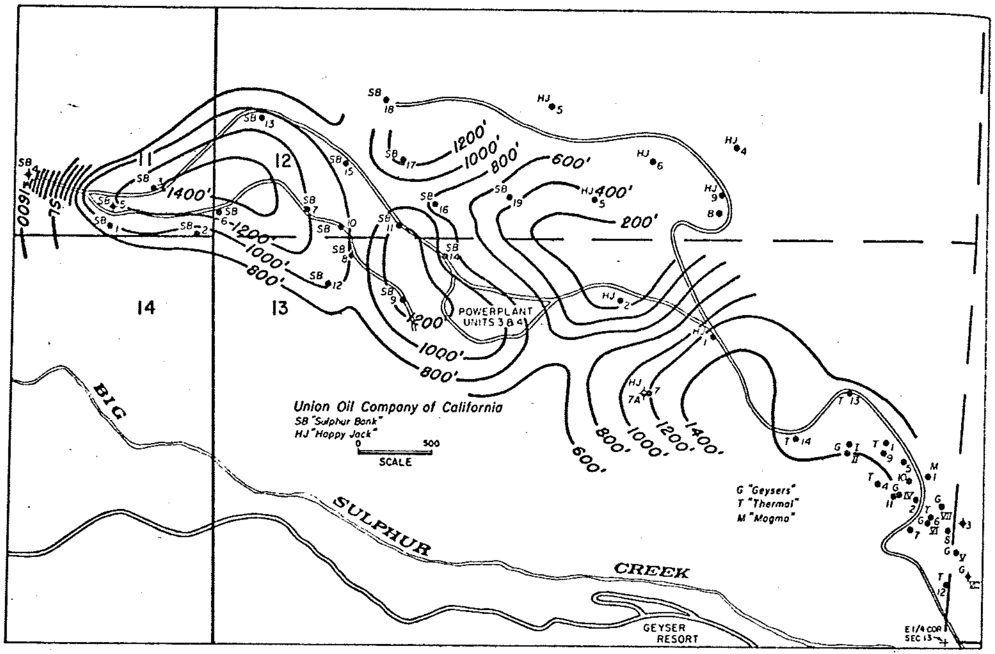
Figure 6. Boiling point/depth curve for The Geysers from White and others (1971).

condensing steam or recharging water. With production, parts of a hot-water geothermal system may become vapor-dominated, as is the case at Wairakei (Grindley, 1965).

The Mayacmas Mountains vapor-dominated system is different geologically from the other proved examples of the type, Larderello and Monte Amiata. At the Italian region, the reservoir is a thick (often exceeding 50 m) body of anhydrite-bearing limestone. The limestone is overlain by an impermeable allochthonous series that provides the lid for the geothermal system. The limestone has a high innate permeability.

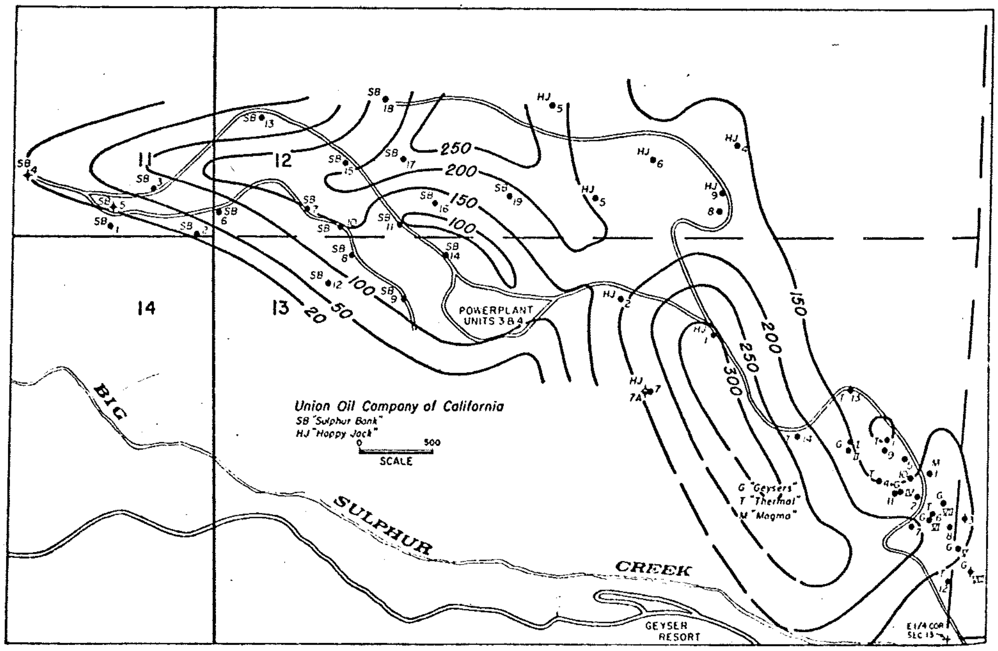
Configuration of the Reservoir at The Geysers and Sulphur Banks

Figures 7 through 12 are constructed from the interpretation of certain parameters obtained during the drilling of the steam wells. *First steam* shows depth, relative to sea level, where steam was first encountered. First steam is not necessarily commercial steam, and the main reservoir lies deeper. The first, uppermost, steam zone is likely to be relatively permeable beds in the upper unit of the Franciscan. *Maximum steam flow* contours isopleths of thousands of pounds of steam per hour. The



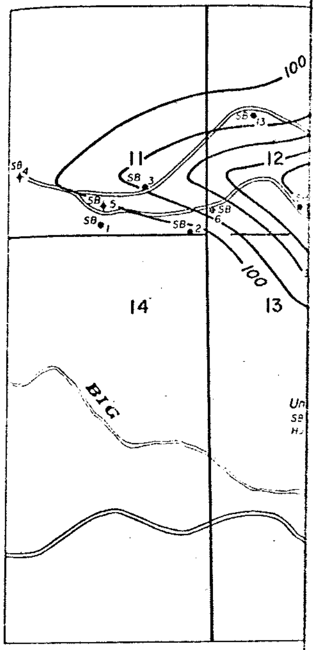
FIRST STEAM

Figure 7. First steam as encountered in wells at The Geysers and Sulphur Bank.



MAXIMUM STEAM FLOW: 000'S #/HR

Figure 8. Maximum flow of steam from wells at The Geysers and Sulphur Bank, thousands of pounds steam per hour.



FLOW ME

Figure 9. Flow measurement

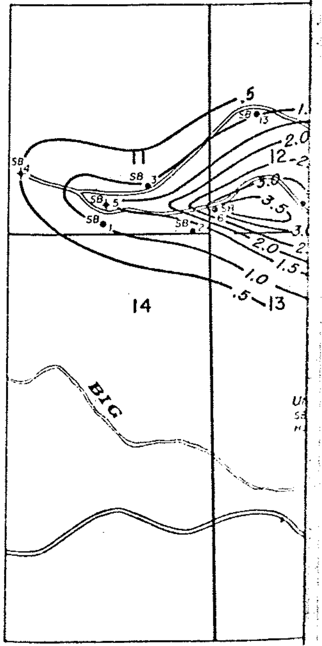


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Figure 10. Absolute shut-in pr
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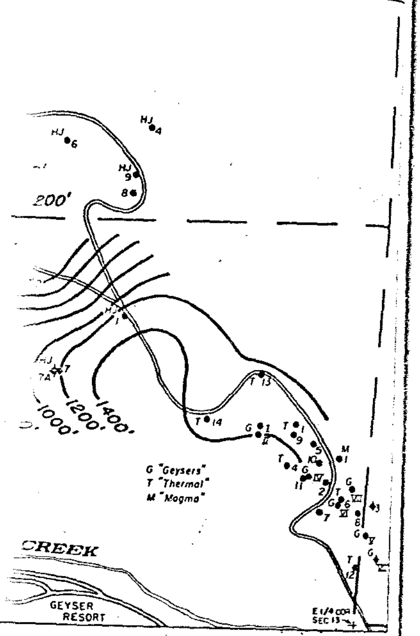

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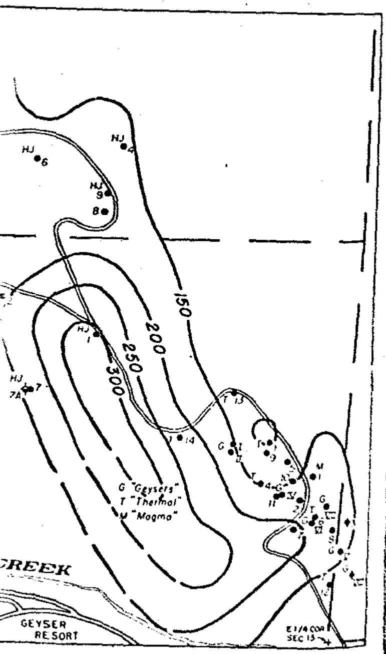

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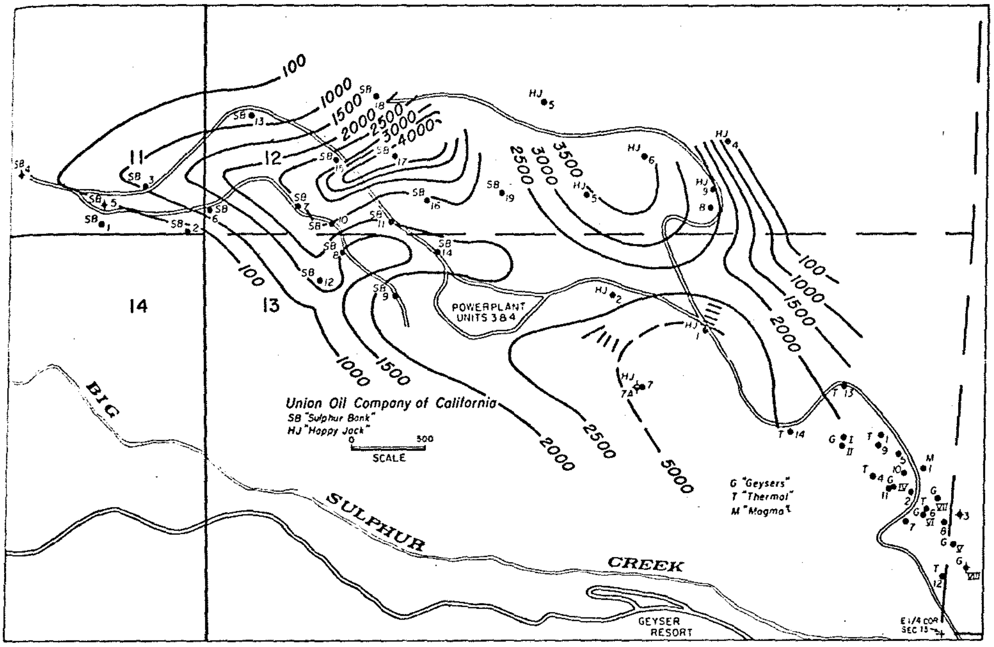
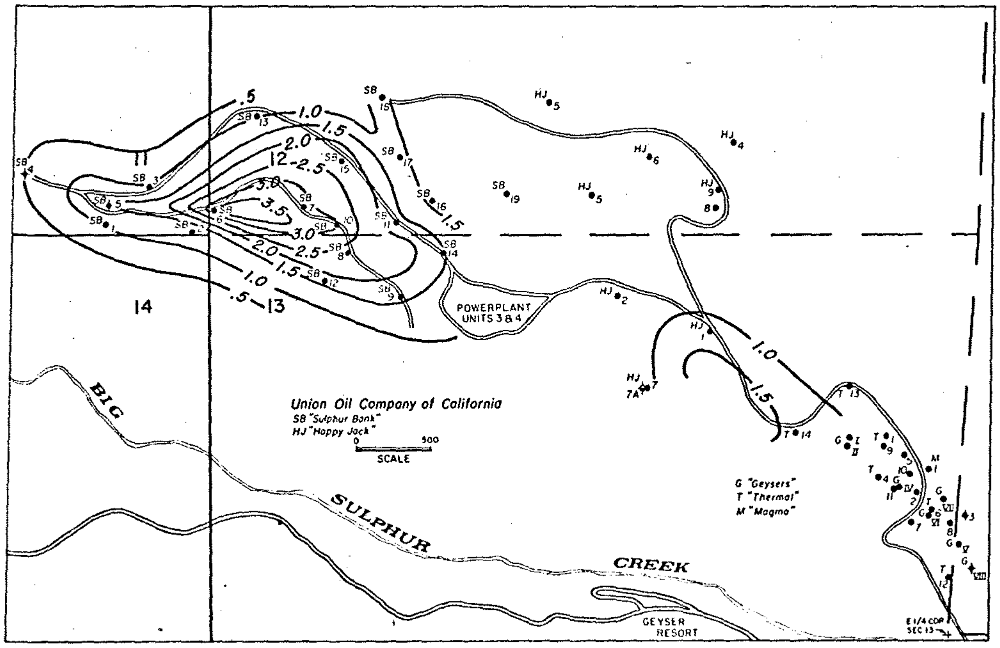


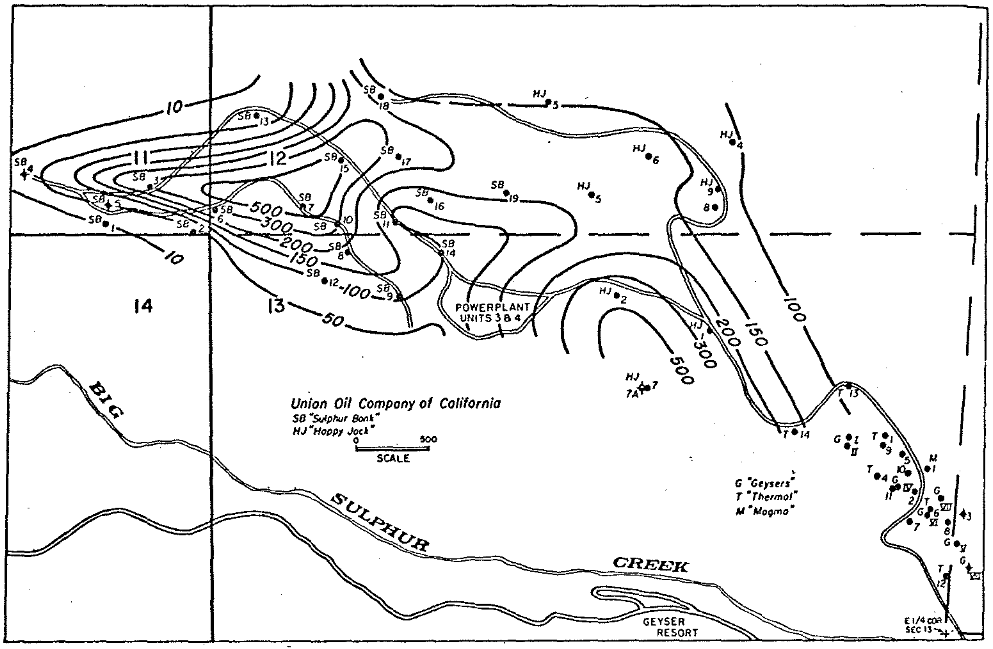
FLOW MEASUREMENT: CROSS SECTIONAL AREA, ORIFICE X WHFP

Figure 9. Flow measurement in wells at The Geysers and Sulphur Bank (derived as described in text).



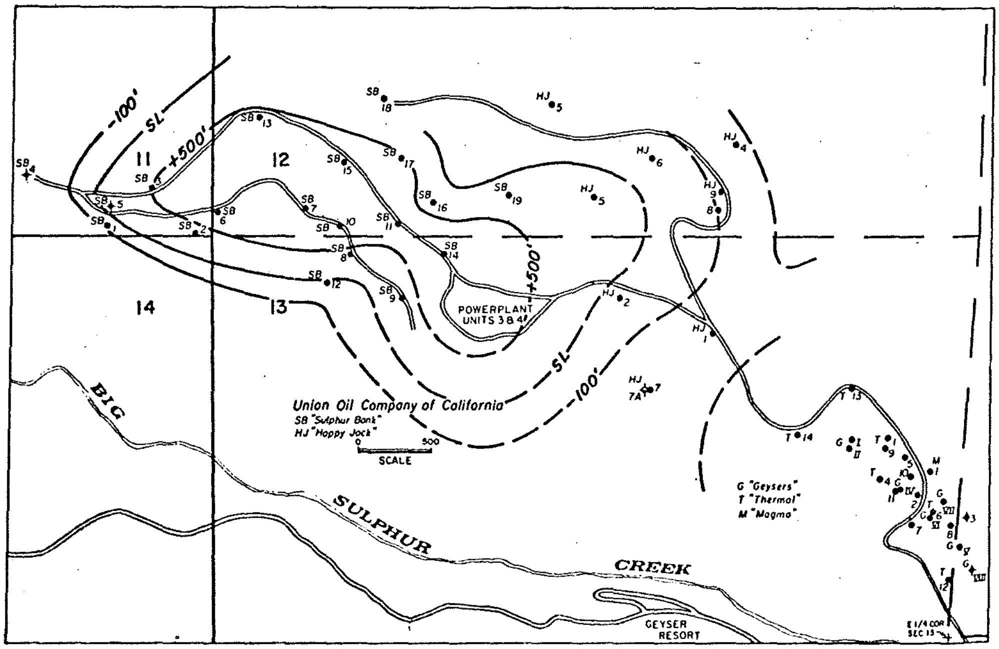
ABSOLUTE SHUT IN PRESSURE AS A FUNCTION OF DEPTH (X10)

Figure 10. Absolute shut-in pressure as function of depth (derived as described in text) of wells at The Geysers and Sulphur Bank.



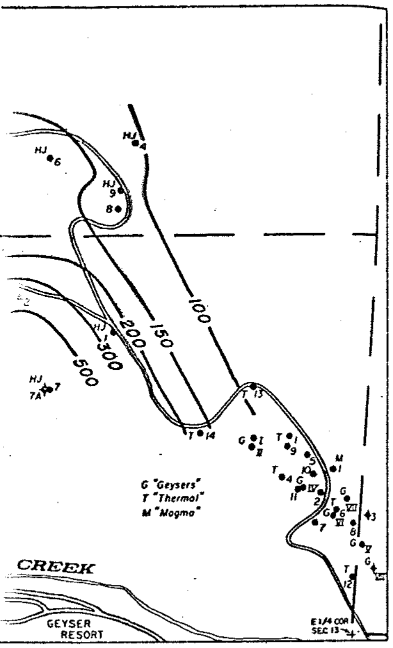
PRODUCTIVE INDEX: STEAM 000'S #/HR ACCORDING TO VOLUME OF HOLE, FIRST STEAM – T. D.

Figure 11. Productive index (derived as described in text) of wells at The Geysers and Sulphur Bank.



CONTOURS ON 'S' CORRELATIVE HORIZON

Figure 12. Contours "S" correlative horizons, Sulphur Bank.
determined from constructed logs at The Geysers and



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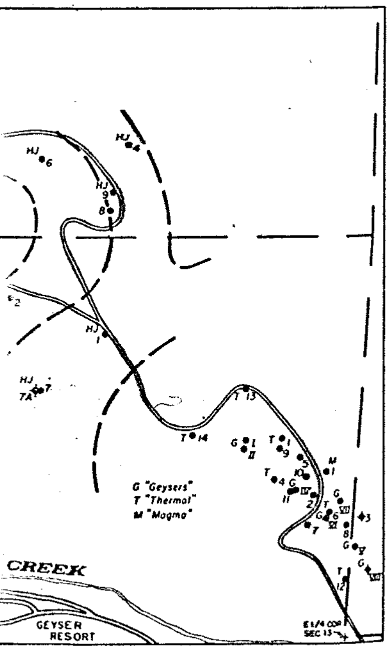

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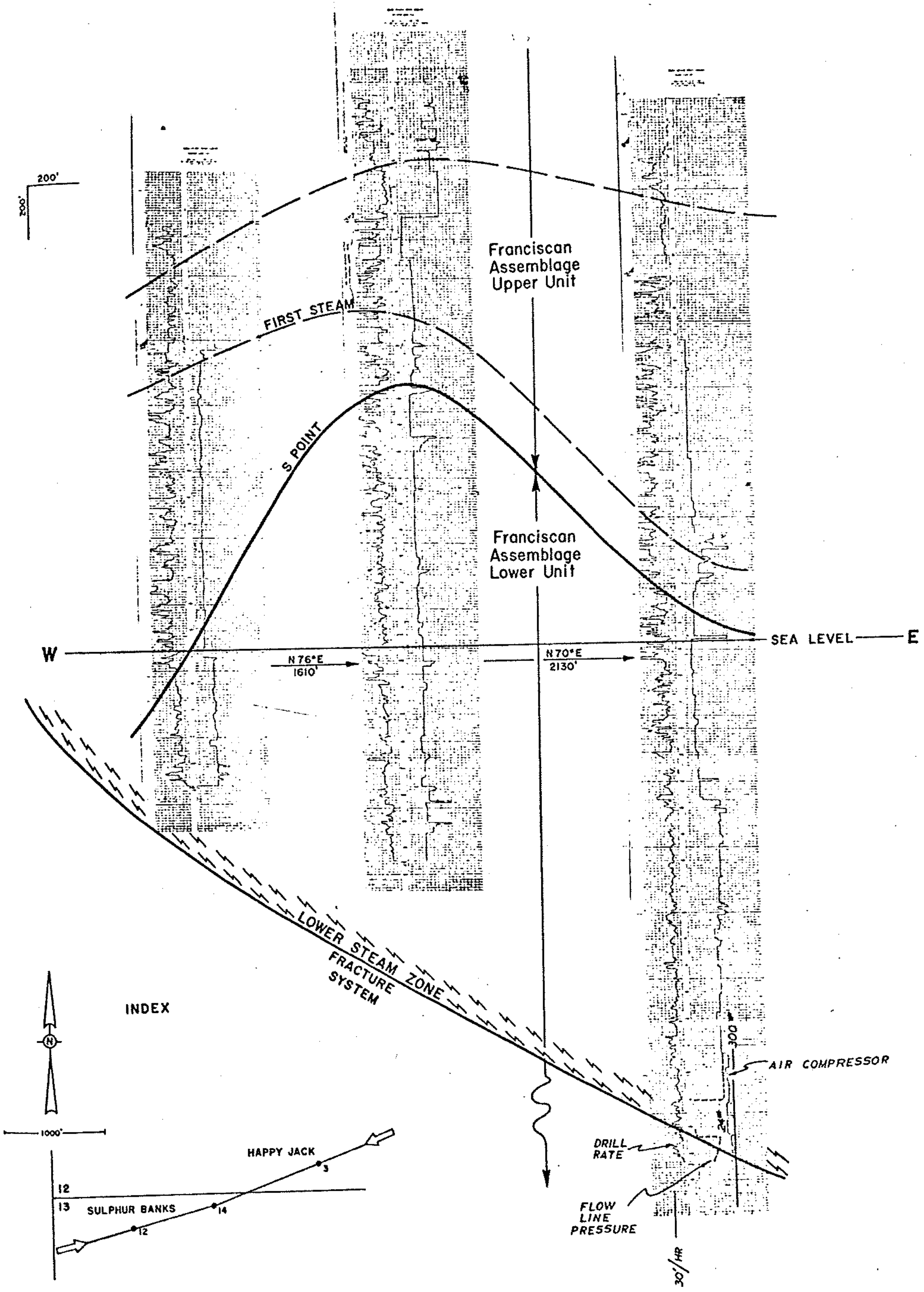

Figure 13. Constructed log section across Sulphur Bank.

depth and hole volume are disregarded. *Flow measurement* is a function of the maximum steam flow and the cross-sectional area of the orifice through which the flow passes. *Absolute shut-in pressure as a function of depth* is empirical, attempting to remove the effect of depth in equating reservoir pressures. The formula used is total depth divided by shut-in pressure times ten. *Productive index* is a measure of the wells' producibility according to volume of hole between first steam and total depth. This attempts to equate productivity in relation to the variables of depth and hole size. *Contours on "S" correlative horizon* show an interpretive structural configuration. This is a correlative marker on mechanical logs constructed of the steam wells.

The cross-section (Fig. 13), made up of some of these constructed logs, shows the "S" horizon as a rudely correlative marker at or near the base of an interval of fast drilling below first steam, and overlying a somewhat homogeneous interval of slower drilling, increasing air compressor demands, and more efficacious steam zones. For convenience, it is taken to be the contact between the upper and lower Franciscan units of McNitt (1968).

First steam, *absolute shut-in pressure*, *productive index*, and *contours* show an elevated trend. An elevated trend mapped by *maximum steam flow* and *flow measurement* is offset to the north, in large part because of deeper drilling here. More steam will be won from a more exposed reservoir.

The elevated trend gains credibility due to the agreement of the parameters and their location on the broken, discontinuous, and commonly masked anticline which is mapped through the area by McNitt (1968). Such an association between structural highs and reservoir potency is seen at Larderello and Wairakei.

Wells encountering what would be classed as large steam flows, above 150,000 lb/hr, encounter such flows in a relatively thick interval near total depth, where pressures are high, as a rule above 30 lb on an 8.75-in. surface flow line. This, the principal reservoir, is a system of shear zones. Working with limited data, it appears as if this interval becomes progressively shallower (relative to sea level) in a southwesterly direction. A reverse fault with a shear zone, upthrown to the east, would also become progressively shallower in this direction.

Behavior of the Reservoir

At the Sulphur Banks and The Geysers, flow and shut-in pressures of the individual wells are affected by periods of common flow or shut-in. The Sulphur Banks well no. 3 recorded an initial steam flow of 85,000 lb/hr with 74 psig flowing pressures. Later, when all the then-completed wells had been continuously producing for three weeks, the flow from this well had declined to 57,000 lb/hr, but the pressure had increased to 85 psig. This well's initial shut-in pressure was 183 psig; after the flow period, it had increased to 195 psig.

Well head flowing pressures tend to increase with decreasing steam flows. There are, however, exceptions, notably the smaller steam flows (Fig. 14).

Shut-in pressures, measured at the surface, range from about 100 to 500 lb (Fig. 15). As little increase in pressure with increasing depth is expected in a vapor, the maximum shut-in pressure is close to the upper range suggested for a vapor-dominated, dry-steam system. The

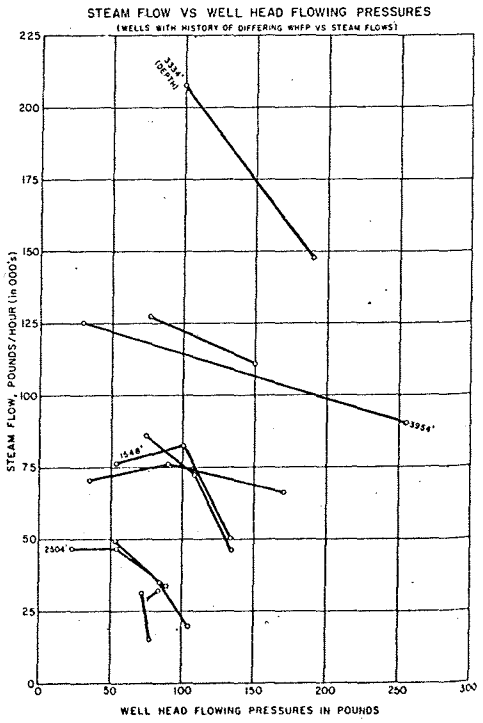

Figure 14. Steam flow *v* flowing pressures for representative wells at The Geysers and Sulphur Bank.

ne Reservoir

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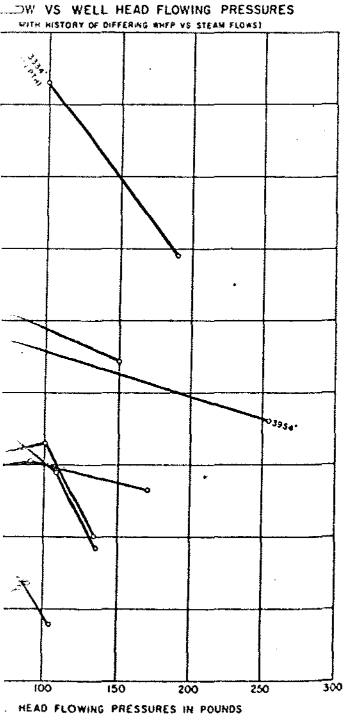

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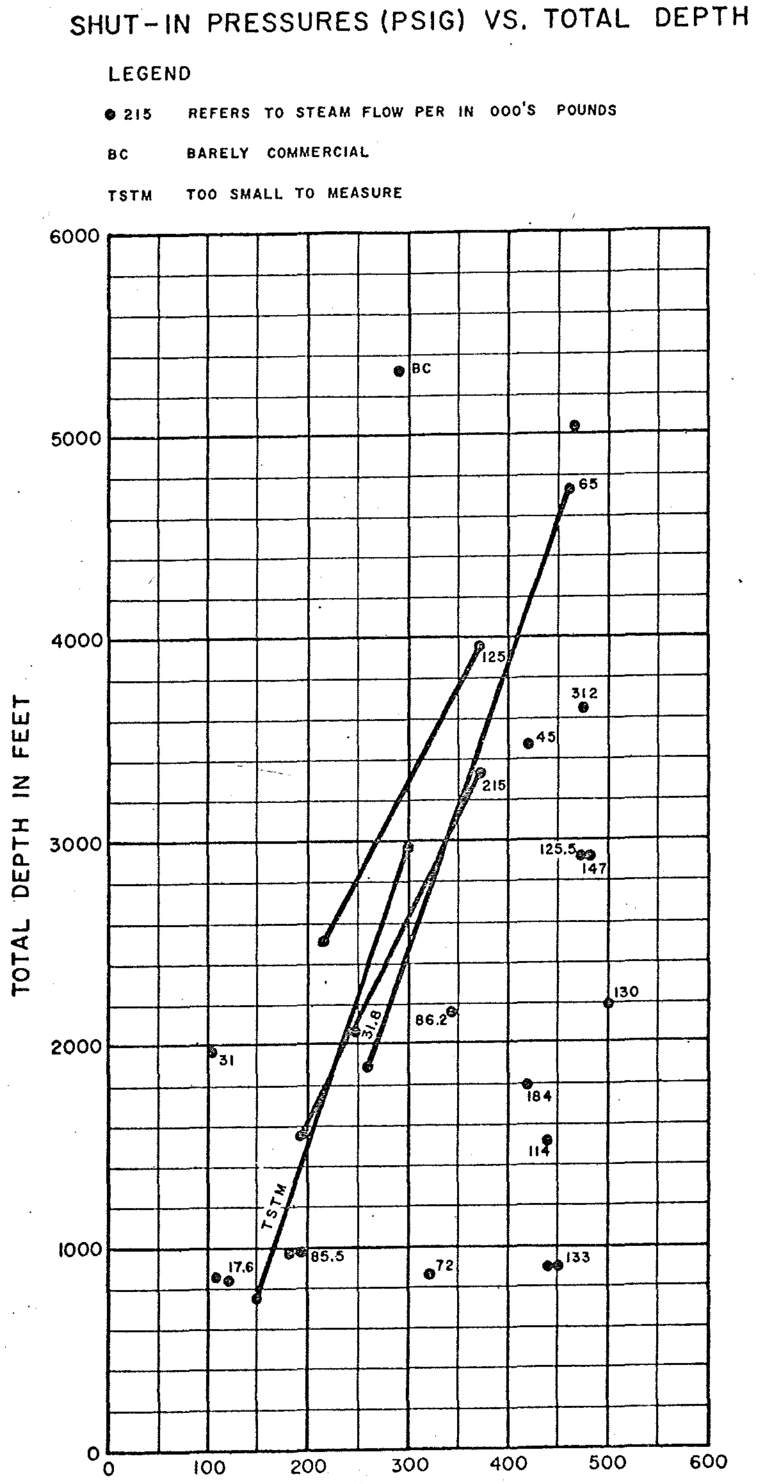

Figure 15. Shut in pressure *v* depth for representative wells at The Geysers and Sulphur Bank.

slight apparent excess can probably be attributed to the presence of other gases. At The Geysers, less than 2 percent of the total vapor consists of gas other than H_2O, the most abundant being CO_2 (White and others, 1971).

Large steam flows tend to occur at high shut-in pressures, although the association is not linear.

In 1968, after an 11-yr production history, a decline of 50 lb was noted at the shallow zone of The Geysers, at depths from 400 to 2,000 ft and probably the upper unit Franciscan lithologic reservoir. Reservoir studies of this zone predict an ultimate recovery of 110 billion lb of steam, from which 47 billion lb have been produced as of January 1968 (Reich and Reich, 1968).

Steam temperatures cluster about a reference boiling-point/depth curve for pure water to a maximum of about 240° C (White and others, 1971; Fig. 6 of this paper). This temperature maximum conforms to the vapor-dominated model. There does not appear to be a direct relation between temperature and rate of flow. Temperature, however, does have a dependence upon steam pressure (McNitt, 1963): temperature increases with increasing pressure. McNitt (1963, p. 15) shows an increase of temperature from 169° C to 188° C accompanying an increase of flowing steam pressures from 59.7 psia to 132.1 psia for three wells at The Geysers.

The temperature/pressure relation is also apparent in static pressures, although this relation again is not linear. In Figure 6, the SB 10 well has a temperature of approximately 233° C; the SB 7, 228° C; the SB 6, 214° C; the SB 3, 197° C; T 10, 186° C; and T 1, 182° C. The maximum initial shut-in pressures for these wells were, in the order above, 460, 450, 320, 195, 140, and 80 lb (psig).

Enthalpies of 1206 and higher Btu/lb are found in the steam reservoirs of the Mayacmas Mountains. As Whiting and Ramey (1969) point out, when liquid and gas coexist in a steam system, the enthalpy of the steam cannot exceed the maximum two-phase envelope enthalpy of 1204.6 Btu/lb. This concept must be modified by regarding the produced steam, only, as being in the vapor state.

While the data are scanty, they suggest that temperatures can in places actually decline with depth, as revealed in drilling experience. The Geysers no. 12 had a bottom hole temperature at 1,450 ft of 109° C, but at total depth, 1,950 ft, the temperature was 102° C. The Sulphur Banks no. 2 had bottom hole temperatures of 185° C at 1,825 ft. These decreased in less than 100 ft more penetration to 149° C. Both these wells were drilled with drilling mud which must have insulated the temperature, but the spread in the Sulphur Banks example particularly is difficult to explain away by simple mud or drilling conditions. A recent example of air drilling, the Signal, McKinley no. 4, measured flow-line temperatures of 126° C when drilling at 5,945 ft. Temperatures decreased to 82° C when at 7,020 ft. Some 400 ft deeper, they were 137° C, declining again to 112° C at total depth of 8,047 ft.

In the Mayacmas Mountains, it is felt that occasions of lower temperatures in the subsurface can be partly due to influxes of cooler, recharging waters. Also, the shear zone reservoirs might be hotter than other sections of the country rock.

A zone nearly saturated with liquid water derived from the condensing steam overlies the reservoir. This zone (McNitt, 1963) has been observed to rise when reservoir pressures were being reduced through discharge and to fall when reservoir pressures were being increased through shut-in. James (1968) suggested that this indicates that the underlying steam reservoir seeks hydrostatic balance.

Current Production and Exploration in Regional Framework

All production to date is directly related to prominent, regionally northwest-trending faulting and its junction with intersecting faults, or as seen in its arcuate, imbricate aspect. Steam production moreover is localized to Mayacmas Mountains blocks that have undergone relatively the most uplift. Except possibly for the shallow zone at The Geysers, production is restricted to the in-bulk impermeable lower unit of the Franciscan. Reservoirs are shear zones associated with the faulting. More shearing exposes more reservoir. Spatially, production to date is located from 7 to 8½ mi south and southwest from Mt. Hannah. This is the youngest volcanic landform, and is marked by a gravity anomaly that conceivably reflects the nearest-to-surface apophysis of the magma heat source.

Certain unsuccessful tests of Signal and Union are located off fault intersections, or else are relatively downdip on blocks between principal regional faulting. The Signal, Wild-

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horse no. 1, recorded flow-line temperatures of 155° C at 4,830 ft and 209° C from 6,500 ft to total depth. Insignificant puffs of steam issued from some of the numerous zones of fast drilling, a quantity of which must represent fissures. These flow-line temperatures are within the range recorded at Castle steam field, but are generally lower than those of The Geysers.

The G.R.I. Rorobaugh area is on the west of the faulting of the Sulphur Bank and The Geysers fields. This development is not as successful as Sulphur Bank, one-half mile away. Some of these wells produce hot water with steam. Considering the Sulphur Bank-Geysers faulting as reverse in nature leads to the conclusion that it does not cut the G.R.I. wells and they therefore do not benefit from it. They are located on the cooler boundary of a vapor-dominated system.

DRILLING PRACTICES

The Grant and Geysers Development wells were drilled with rotary equipment, the steam in the bore hole being controlled by injected streams of cold water. Surface pipe (usually 10-in. diam.) was set as far as possible into hard rocks. Drilling progressed until the steam flow was sufficiently large to warrant the setting of an intermediate string (usually 8 in. diam.). The well was then drilled beyond to total depth as an uncased, open hole.

The first Magma-Thermal wells were drilled conventionally with rotary equipment and drilling mud. The string usually included perforated casing opposite the steam zones, as in early oil-field practice. The mud, baking on down-hole hot surfaces, was found to inhibit steam flow, and starting with the Geysers no. 7, drilling was carried on with air below the surface pipe. Hole for conductor and surface pipe, however, was still drilled with mud.

For shallow wells, conductor and as much as 500 ft of surface pipe (usually 10¾ or 13⅜ in.) are set, and the well is uncased and open to total depth (usually 9⅞-in. hole). In deeper wells, hole size is commonly reduced near the final third of penetration. Later deep wells normally set conductor and surface pipe as well as an intermediate string at depths from 2,000 to 4,000 ft.

Air, the circulating medium for drilling, is produced by compressor banks. The recent Signal wells use four compressors, of which three are used and one is kept on standby. Each is capable of putting out some 900 cu ft/min. This is sufficient to carry cuttings up the annulus to be blown out the flow line. Drilling beyond the producing zone is carried on under a condition of "controlled blowout" (Hunnicutt, 1970). The mass flow of even a 100,000 lb/hr steam well will carry abrasive cuttings from the bit that can destroy a drill string in a few hours (Hunnicutt, 1970).

Drilling times for representative deep wells are shown on Table 2.

Drilling is expensive, a 6,000-ft range test costing $150,000 or more. Completion equipment is a minor additional expense. Electrical logging of steam wells is not practical because of the extreme heat down-hole, except that operators sometimes electrically log the upper portion of the bore through which surface or intermediate pipe is to be set.

Steam zones are often identified by fast drilling and a surge from the air compressors in reaction to a steam flow.

The problem of disposal of borated waters from the condensing generators arose in 1968. In 1969 the suspended Sulphur Banks no. 1 was tested for water disposal. Injection rates of up to 10,000 barrels per day had no apparent effect on nearby steam producers. The operator ultimately drilled a separate disposal well one-quarter mile to the west of Sulphur Banks.

STEAM RESERVES

Reserves of producible steam should be thought of as being measured by the life of the system. The geothermal system should endure as long as heat is being supplied by the source, withdrawal of steam does not exhaust the thermal fluid, the system is recharged, and the essential nature of the *reservoir* and *cap* does not change. Nevertheless, with continuing draw-off, the steam reservoir will undergo some change.

Material and energy balance reservoir calculations have been applied to Wairakei (Whiting and Ramey, 1969). The pressure drop

TABLE 2. REPRESENTATIVE DRILLING TIMES

Depth (in feet)	Days drilling
4,868	19
4,900	18
5,812	29
5,949	38
6,277	27
7,254	30
7,532	53

in the shallow zone at The Geysers permits a pressure/cumulative estimation of reserves there.

The operator at The Geysers and Sulphur Banks has not released reservoir performance data. It is presumed that he has conducted flowing and static pressure/cumulative tests.

Larderello has been experiencing a general decline in pressure and output, with scanty data suggesting an increase in temperature (Ente Nazionale per l'Energia Elettrica, 1971). A continuous drilling program is necessary to sustain the required steam flows for its 365.1 MW generating capacity. Production and power generation have risen from first production in 1913 to the present (2.587 million kwh in 1969). This growth is in part due to exploitation of the entire boraciferous region, with the development of new, often separated producing areas within the hydrothermal province.

The Mayacmas Mountains province's actual *capability*, measured in steam producibility, is at present higher than the projected generating *capacity* of 600 MW. The ultimate capability might be in the 2,000 MW to 5,000 MW range. The life of the system can be measured in increments of a century. The expected life multiplied by the median projected capacity would give approximate "reserves."

BRIEF ECONOMICS OF GEOTHERMAL STEAM

Purchase Price of Steam

The original purchase price for steam at units 1 and 2 at The Geysers was 2.5 mills/kwh. For additional units, the price is calculated yearly on the basis of a weighted average of 2.5 mills adjusted for current fuel costs and the best heat rate for fossil fuels compared with the December 1958 fuel costs and the best heat rate and the average nuclear fuel costs. Recently, .14 mills was awarded the operator for his undertaking to dispose of condensate from the plant.

Production Expenses

The production expenses, including purchase price, average 5.65 mills/kwh for units 1 and 2. The figure is 4.71 mills for units 3 and 4. New units 5 and 6 are designed to operate at 4.38 mills/kwh at 90 percent plant factor, 5.02 mills at 70 percent, and 5.51 mills at 60 percent. The average of the three plants at 90 percent is 4.91 mills/kwh. Subtracting the steam purchase price results in a generating cost of 2.27 mills/kwh.

Using units 3 and 4 as an example, the net yearly production at 90 percent is 44,150,400 kwh. At 4.71 mills per kwh, the yearly production expense would be $207,948, or annual production costs of $2.12 per kilowatt.

Plant Costs

The capital cost of the 26 MW units 1 and 2 is $3,800,000 or $146 per gross kilowatt installed; for the 56 MW units 3 and 4, the cost is $6,900,000 or $123 per gross kilowatt.

Steam Conversion

In practice at The Geysers and Sulphur Bank, 18.53 lb of steam will produce 1 kwh. Huge volumes of steam are utilized in geothermal plants in contrast to a fossil fuel plant. In this sense, a geothermal generating plant may have a low efficiency (for example, 14.3 percent for unit 3).

History of Generation

The following (Table 3) is a 10-yr history of electrical generation (*courtesy* Pacific Gas and Electric Co.).

Incremental Benefits

Geothermal power is incremental; that is, plants can be augmented as producing capability is increased. Hydroelectric and fossil fuel plants, in contrast, must be built up at first to maximum anticipated use.

TABLE 3. NET ANNUAL ELECTRICAL GENERATION FOR TEN YEARS 1960 TO 1970 AT THE GEYSERS AND SULPHUR BANK

Year	Annual net generation (MW hours)
1960	33,750
1961	94,504
1962	100,461
1963	167,953
1964	203,790
1965	189,210
1966	188,001
1967	316,310
1968	435,827
1969	614,710
1970	525,177
Total	2,869,693

Note: Units 3 and 4 at Sulphur Bank on stream 1967.

Retail Value

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NET ANNUAL ELECTRICAL GENERATION
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100,461
167,953
203,790
189,210
188,001
316,310
435,827
614,710
525,177
2,869,693

3 and 4 at Sulphur Bank on stream 1967.

Retail Value

The retail market value of 1,000 kwh in California is $360 per day. One kilowatt therefore is worth 1.5¢. Therefore, 18.53 lb of steam are worth in retail value equivalent, 1.5¢; one pound of steam is worth .081¢. Union Oil Co. equates a 100,000 lb/hr steam well to a 200 barrel of oil per day well in energy terms.

Future Projections

By 1975, an incremental 600,000 kwh capacity is projected for the area developed by Union Oil Co. The natural producing potential of the Mayacmas Mountains geothermal province is estimated, however, to be many times this figure.

Comparison to Other Forms of Electrical Generation[3]

Production Expense. The Geysers: 2.27 mills/kwh; steam-electric (1968 weighted average): 3.43 mills/kwh; hydroelectric (1968 weighted average): .53 mills/kwh. Despite the higher production expense in geothermal plants compared to hydroelectric, the annual production costs are lower, $2.12 per kilowatt compared to $2.72 per kilowatt for hydroelectric plants.

Plant Costs. The Geysers (average of units 1 through 4): $130 per kilowatt installed; steam-electric (three selected plants about equivalent in size to pairs at Sulphur Bank and The Geysers): 70 MW–$182, 73.4 MW–$157, and 50.5 MW–$176 per kilowatt installed; hydroelectric (average of 21 U.S. systems in 1968): $270 per kilowatt installed.

Plant Factor. The Geysers and Sulphur Bank: 90 percent by design; steam-electric (average in U.S. 1968): 54 percent; hydroelectric (average of 21 U.S. systems in 1968): percent.

Geothermally generated electrical power is thus competitive with or superior to other forms of generation.

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[3] Data concerning steam-electric and hydrothermal systems are taken from Federal Power Commission annual supplements and are not cited in the references.

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Subaqueous
Cretaceous

ABSTRACT

Delta-front sedimen
tion of the Cretaceous
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Brazil. The Pitanga M
three sedimentary fa
ences in lithology an
whereas the Caruaçu
ten such facies.

The three sedimen
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by mass flow and
loss; and (3) Dish-st
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and steplike load st
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