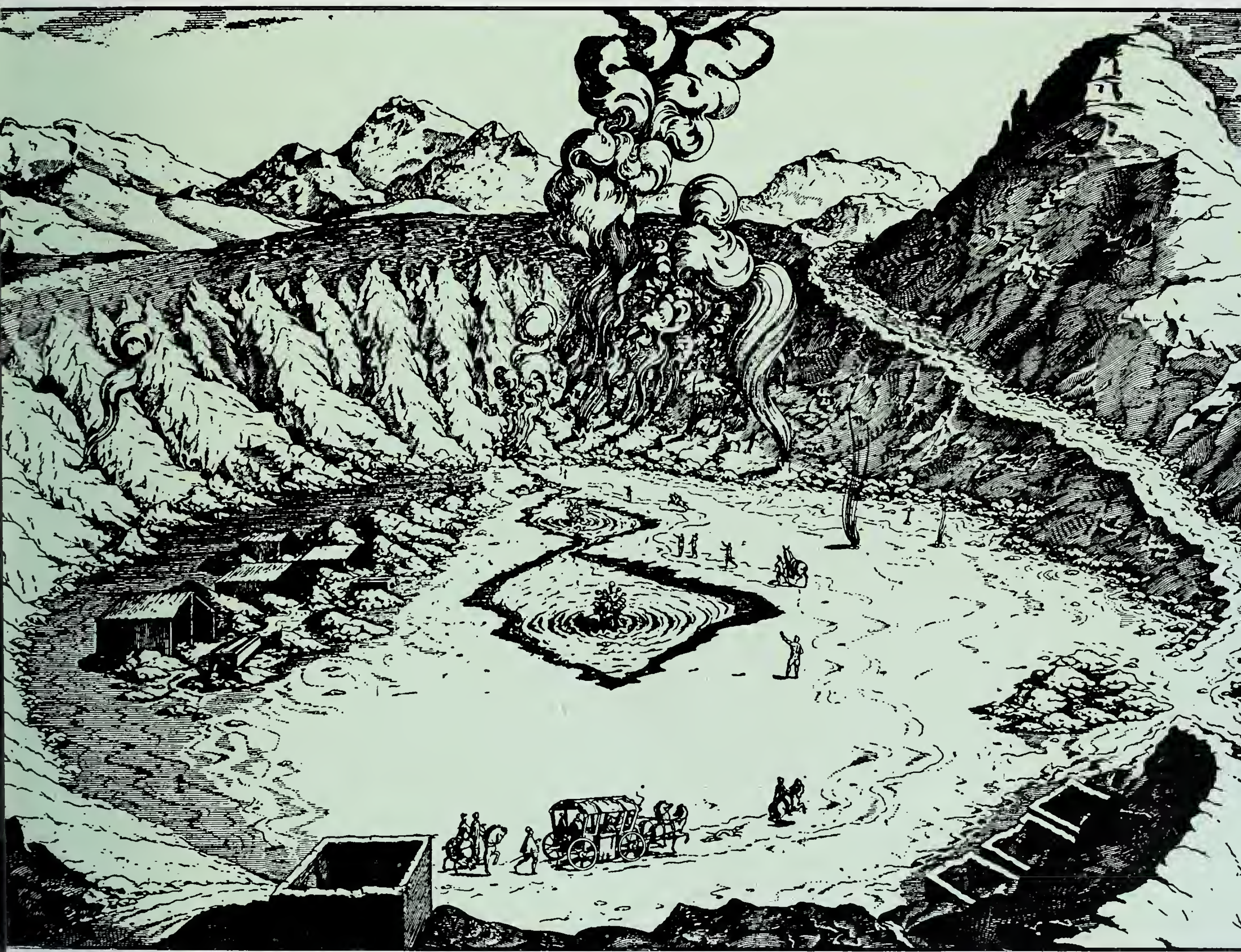
Exploration and Development of

GEOTHERMAL POWER

In California



SPECIAL REPORT 75

CALIFORNIA DIVISION OF MINES AND GEOLOGY
FERRY BUILDING, SAN FRANCISCO, 1963

Cover. Solfatara, southern Italy. The road to Naples once ran past the hot springs of Solfatara, where there was a perpetual bubbling and fuming of sulfurous waters. This illustration, which was made in the early part of the eighteenth century, shows the hot springs area. The sheds to the left were used for the extraction of alum.

EXPLORATION AND DEVELOPMENT OF GEOTHERMAL POWER IN CALIFORNIA

By JAMES R. McNITT, Mining Geologist
California Division of Mines and Geology

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CONTENTS

Geyser steam field seen through expansion bend in 2,000-foot steam line which transports steam from the field to the plant. *Photo courtesy Pacific Gas and Electric Company.*

ILLUSTRATIONS

Photographs

Figures

Figures—Continued

LAGO, ITALY, 1850.

ABSTRACT

From 1955 to 1962, approximately 40 wells were drilled in 15 California thermal areas for the purpose of exploring and developing natural steam to utilize for electric power generation. Twenty-four of the wells were drilled in the three areas which at present seem to have the greatest potential for the production of natural steam: The Geysers, Sonoma County; Casa Diablo, Mono County; and the Salton Sea area, Imperial County.

Since June 1960, steam from The Geysers thermal area, produced at a rate of approximately 250,000 lb/hr, has been utilized to operate a 12,500 kw generating unit. Completion of a second generating unit, now under construction, will increase the total capacity of this area to approximately 28,000 kw. Geologic mapping and interpretation of temperature and pressure data from the steam wells suggest that superheated steam is confined in a steeply dipping fracture zone by an overlying body of ground water. The fracture zone is part of a complex system of normal faults which defines a graben structure at least 5½ miles long and about 1 mile wide. The density inversion represented by the steam phase underlying the water phase in the fracture zone is attributed to the thermodynamic equilibrium existing between the two phases in an open system.

The Casa Diablo thermal area is located on the southwest side of a volcano-tectonic collapse structure which is approximately 23 miles long and 12 miles wide. Vertical displacement within the collapse structure may be as much as 5,000 feet on the west side and 18,000 ± 5,000 feet on the east side. Four of the tested wells, drilled to depths ranging from 570 to 1,063 feet, flow saturated steam at rates ranging between 19,000 and 69,300 lb/hr at 7.5 to 39 psig wellhead pressure.

The Salton Sea thermal area is located in the vicinity of five small volcanic domes on the southeast shore of the sea. The elevation of the sea, 240 feet below sea level, indicates that it occupies a tectonic depression. Positive gravity and magnetic anomalies suggest the presence of a large intrusive body beneath the volcanic domes. A 5,230 foot well, drilled over this anomaly in late Tertiary and Quaternary sediments, flowed 123,000 lb/hr steam and 457,000 lb/hr concentrated brine at 200 psig wellhead pressure.

In light of the above data, and data now available from foreign projects, three fundamental problems of geothermal power development can be considered: a) preliminary evaluation of a thermal area; b) location of exploratory wells; and c) estimation of steam reserves. Preliminary evaluation of an area usually is based on natural surface heat flow. Experience to date, however, has shown that by drilling wells in a thermal area, heat flow has been increased 3 to 170 times the observed natural surface heat flow, depending on the permeability and structural characteristics of the thermal fluid reservoir, as well as the initial enthalpy of the thermal fluid. The efficiency of well location can be greatly increased by regional and local tectonic analyses based on geologic mapping and geophysical methods, including gravimetric, magnetic, resistivity, and thermal. Steam reserves and life expectancy of the field depend on rates of heat and fluid flow in an open system rather than on the more familiar condition of mechanical equilibrium associated with the more or less closed system of a petroleum reservoir.

INTRODUCTION

Geothermal power is the electric energy generated by the utilization of natural steam. This power is harnessed by releasing steam from natural thermal areas through bore holes and conducting it through a system of pipe lines to a turbine-generator unit.

The potential of geothermal energy was first recognized in Italy, where the first steam well was drilled at Larderello in 1904. By the late 1930s, the steam fields were producing electric power at a capacity of 100,000 kw. The generating plants were destroyed during World War II, but they have been rebuilt and expanded so that the present capacity is in excess of 300,000 kw.

The second country to investigate the possibilities of geothermal power was New Zealand. The necessity for rapid development of power resources during the post-war period prompted the New Zealand government to initiate a geothermal power project at Wairakei, North Island, in 1950. Development has progressed to the stage where plants having a total capacity of 192,000 kw have been authorized. These plants are being constructed in two stages. The first stage (69,000 kw) was completed in March 1960, and the second stage (123,000 kw) is scheduled for completion in 1963. Tentative plans have been prepared for later expansion of the installation to a total capacity of 282,000 kw.

Encouraged by the progress of geothermal power development in Italy and New Zealand, exploration and development programs recently were initiated in Iceland, Mexico, El Salvador, Japan, Russia and the United States. By 1961, various development programs in these countries included the proposal of a 15,000 kw geothermal power station in Iceland, the operation of a 3,500 kw pilot plant to test wells of the Pathé field in Hidalgo, Mexico, and the operation of a 12,500 kw power station at The Geysers in California.

The Geysers plant, located in northern Sonoma County, went on stream in June, 1960. In April 1962, construction began on a second generating unit which will raise the capacity of the plant to approximately 28,000 kw. The success of this power project has greatly stimulated exploration for natural steam throughout California and Nevada, as well as in some areas of Oregon, New Mexico, and Hawaii.

The value of geothermal power exploitation is greatest in the California and Nevada desert regions, where neither fossil fuels nor hydroelectric power is available. But even in those regions where hydroelectric and steam generating plants are feasible, geothermal power offers considerable economic advantages: there is no fuel cost in comparison with the more conventional steam generating plant, or those utilizing atomic energy; and the capital investment needed to develop a steam field is, in most cases, smaller than that needed to construct either hydroelectric or conventional steam-generating facilities of the same capacity.

In August of 1961, an international conference was held under the auspices of the United Nations for the purpose of collecting and exchanging data on "New Sources of Energy," including geothermal power. The ultimate objective of the conference was to make this widely dispersed, and mostly unpublished, information available for the use of underdeveloped countries, for whom geothermal power is of particular economic advantage. Thirty-nine papers on the geologic investigation of geothermal fields and 28 papers on the harnessing of geothermal energy were presented. A considerable amount of the information discussed in the second part of this report was obtained from the papers presented at the United Nations conference.

The writer also wishes to acknowledge the cooperation of the Magma Power Co. of Los Angeles and its affiliates, the Thermal Power Co. and the Natural Steam Corporation; the Pacific Gas and Electric Co. of San Francisco; O'Neill Geothermal Inc. of Midland, Texas, and the Rogers Engineering Co. of San Francisco for making available much of the data presented in Part I of this report.

PART I. CALIFORNIA STEAM FIELDS

As of November 1962, 15 thermal areas have been drilled in California (figure 1). Table 1 lists the number of wells drilled in each area as well as other pertinent data. The temperatures listed in Table 1 were measured with maximum-recording thermometers, except at The Geysers, where test-metals of known melting points were used. The temperature listed is the maximum temperature recorded in the well or group of wells drilled in each area and does not correspond, in every case, to the temperature measured at the greatest depth reached by the drill.

Because the successful development of power at The Geysers, and the well-test data from Casa Diablo and the Salton Sea have confirmed the economic potential of these three thermal areas, they will be described in detail. Although hot water or steam has been encountered in most of the wells drilled in the other 12 thermal areas listed in Table 1, data from these areas are as yet insufficient for determining whether an adequate supply of steam will be available for power production.

Photo 1.
The Geysers steam field,
Sonoma County, California.
Photo courtesy Pacific Gas and Electric Company.

THERMAL AREAS

1. Lake City
2. Cedarville
3. Terminal Geyser
4. Wendell
5. Amidee
6. Sulphur Bank
7. The Geysers
8. Calistoga
9. Fales Hot Springs
10. Bridgeport
11. Casa Diablo Hot Springs
12. Casa Diablo Hot Pool
13. Tecopa Hot Springs
14. Randsburg
15. Salton Sea thermal area

Table 1. Thermal areas drilled in California as of November 1962.

Thermal area	Location	Number of wells drilled	Greatest depth reached, feet	Maximum temperature measured, degrees C	Date when drilled	Wells drilled by
1. Lake City	Modoc Co., Secs. 23 & 24, T. 44 N., R. 15 E.	4	2,150	160	1959-1962	Magma Power Co. (and assocs.)
2. Cedarville	Modoc Co., Sec. 6, T. 42 N., R. 17 E.	1	734	54	1962	Magma Power Co. (and assocs.)
3. Terminal Geyser	Plumas Co., Sec. 36, T. 30 N., R. 5 E.	1	1,270	129	1962	Geysers Steam Co.
4. Wendell	Lassen Co., Sec. 23, T. 29 N., R. 15 E.	1	630	79	1962	Magma Power Co. (and assocs.)
5. Amidee	Lassen Co., Secs. 8 & 5, T. 28 N., R. 16 E.	3	1,116	107	1962	Magma Power Co. (and assocs.)
6. Sulphur Bank	Lake Co., Sec. 5, T. 13 N., R. 7 W.	2	1,391	186	1961	Magma Power Co. (and assocs.)
7. The Geysers	Sonoma Co., Secs. 13 & 14, T. 11 N., R. 9 W.	22	2,100	300 (approx.)	1921-25, 1955-57 1959-61	Geyser Development Co. (1920-25) Magma and Thermal Power Cos. (1955-61)
8. Calistoga	Napa Co., Sec. 26 (projected), T. 9 N., R. 7 W.	3	2,000	137	1960-61	Calistoga Power Co.
9. Fales Hot Springs	Mono Co., Sec. 24, T. 6 N., R. 23 E.	1	413	--	1962	Magma Power Co. (and assocs.)
10. Bridgeport	Mono Co., Sec. 9, T. 4 N., R. 25 E.	1	982	51	1962	Magma Power Co. (and assocs.)
11. Casa Diablo Hot Springs	Mono Co., Sec. 32, T. 3 S., R. 28 E.	9	1,063	178	1959-62	Magma and Natural Steam Corp.
12. Casa Diablo Hot Pool	Mono Co., Sec. 35, T. 3 S., R. 28 E.	1	805	134	1961	Magma and Natural Steam Corp.
13. Tecopa Hot Springs	Inyo Co., Sec. 33, T. 21 N., R. 7 E.	1	422	--	1962	Magma Power Co. (and assocs.)
14. Randsburg	San Bernardino Co., Sec. 25, T. 29 S., R. 41 E.	1	772	116	1960	Magma Power Co. (and assocs.)
15. Salton Sea thermal area	Imperial Co., Sec. 23, T. 11 S., R. 13 E. and Sec. 10, T. 12 S., R. 13 E.	7	5,232	340	1927, 1957-58, 1961-62	Pioneer Development Co. (1927) Kent Imperial Oil Co. (1957-58) O'Neill Geothermal Inc. (1961-62) Western Geothermal (1962)

Figure 1. (Opposite page.) Map showing location of thermal areas drilled in California to November, 1962.

Photo 2.
The Geysers power plant, aerial view.
Power plant under construction in lower right.
Photo courtesy Pacific Gas and Electric Company.

THE GEYSERS

The Geysers thermal area is located approximately 75 miles north of San Francisco on Big Sulphur Creek in the Mayacmas Mountains of northern Sonoma County. This area is distinctive for two reasons: it is the only field outside of Italy which produces dry steam, and it is the only field in the United States developed to the point of actually producing electric power.

Geology

The Mayacmas Mountains of northern Sonoma County are underlain by the Jurassic-Cretaceous Franciscan Formation which is a eugeosynclinal sequence of graywacke, shale, spilitic basalt, and serpentine. The oldest unit in this sequence is a massive graywacke with a very minor amount of shale. The graywacke is overlain by several hundred feet of spilitic basalt and associated chert beds. The basalt is in turn overlain by a sequence of poorly bedded graywacke and shale (ratio approximately 1:1). Conformable bodies of serpentinized peridotite, in places over 200 feet thick, occur at the upper and lower contacts of the basalt. Bodies of hornblende and glaucophane schist are found near basalt-serpentine contacts and are thought to be the product of contact metamorphism of basalt by ultrabasic intrusions. Complex faulting, however, has obscured the original schist contacts.

Geosynclinal deposition ceased in early Tertiary time when the Mesozoic rocks were uplifted and gently folded. There is no record of the Oligocene and Miocene epochs in this area, but by Pliocene time the uplifted rocks had been truncated by erosion. In the Pleistocene, volcanic rocks, including rhyolitic flows and tuffs, obsidian, basaltic lavas, and lavas of dacitic and andesitic composition, were erupted onto the eroded surface. These Pleistocene volcanic rocks —the Clear Lake volcanic series of Brice (1953)— principally occupy the Clear Lake basin, which borders the Mayacmas Mountains on the northeast. This basin is a northwest-trending structural depression 30 miles long by 15 miles wide.

Approximately contemporaneous with the development of the Clear Lake basin, the Mesozoic rocks of the Mayacmas Mountains were uplifted and complexly faulted into a series of northwest-trending horsts and grabens. The individual horsts and grabens range between 1 and 2 miles in width and retain their identity as structural units for lengths up to 10 miles.

The grabens have not subsided on distinct major faults, but movement has occurred along numerous, inter-related normal faults, which dip between 60° and 80°. The fault traces are distinctly arcuate, having the downdropped block on the concave side of the fault. The lengths of the individual faults rarely exceed 1 mile. The grabens are also complexly cross-faulted by arcuate faults which define small downdropped units within the individual grabens. These units may be roughly circular, having diameters ranging from half a mile to a mile, or they may be oblong, having their long axes at various angles to the sides of the major graben in which they occur.

Because of the complexity of the faulting, the lack of clearly recognizable datum planes, and the variable thickness of the faulted units, it is difficult to measure accurately the amount of vertical displacement. The order of magnitude of this movement, however, may be estimated from one of the grabens in which Tertiary gravels have been downdropped into the underlying Mesozoic rocks. The minimum vertical displacement of this gravel unit is 2,200 feet, with the movement distributed among two or three normal faults.

The Geysers thermal area is at the west end of a northwest-trending graben, 5½ miles long by 1 mile wide, which is 5 miles southeast of the Clear Lake basin. Numerous thermal areas, of which The Geysers is the largest, occur within the graben. The Geysers graben is flanked on the northeast by Cobb Mountain, a horst block capped by a rhyolite extrusion. Cobb Mountain is bordered on the southeast by a small graben containing two thermal areas, Castle Rock and Anderson Springs. The majority of thermal areas in the Mayacmas Mountains are located in the Geysers and Anderson Springs grabens. Cobb Mountain represents the culminating uplift of the Mayacmas range. Because this uplift corresponds with a volcanic extrusion center and is spatially associated with the thermal areas, it is possible that forceful magmatic intrusion is responsible for the uplift of Cobb Mountain, and that the flanking grabens were formed due to horizontal extension of the crust across the arched area.

Figure 2 (p. 22-23) is a geologic map of part of The Geysers graben. In this area Franciscan graywacke is overlain by basalt, which in turn is overlain by a body of serpentine. Along the canyon of Big Sulphur Creek both the serpentine and basalt have been downfaulted into the underlying graywacke, with the serpentine body marking the axis of the graben. The geometry of the faults and the relative stratigraphic position of the faulted units indicate that the thermal areas are located on the fissures closest to the serpentine body. This body marks the fault block which has undergone the greatest amount of subsidence.

The fact that thermal springs occur mainly on the southwest side of the serpentine unit rather than being equally distributed on both sides of this central block probably reflects the pattern of ground water flow. The fault traces on the southwest side of the serpentine are considerably lower in elevation and closer to the bed of Big Sulphur Creek than the fault traces on the northeast side of the serpentine. This difference in elevation produces a sloping ground water table which intersects the ground surface close to the elevation of Big Sulphur Creek.

Thermal activity

The Geysers thermal area, as defined by the effects of hydrothermal rock alteration at the surface, is about 1300 feet long by 600 feet wide. The longer dimension approximately parallels the northwest-trending fault block into which the steam wells are drilled (figure 2).

Most of the natural thermal activity is confined to Geyser Creek, which occupies a narrow canyon crossing the western part of the thermal area from north to south. Although this canyon contains numerous hot springs, whose temperatures range between 50° C. and the boiling point, there are only two rather feeble fumaroles. A third fumarole, also quite small, plus a few hot springs occur in the drilled area just to the east of Geyser Creek.

Allen and Day (1927, p. 30) measured the discharge from hot springs in Geyser Creek and found the flow to range between 2,770 gal/hr in the wet season and 1,775 gal/hr in the dry season. Because these authors estimate this discharge to be "at least half if not considerably more" than the total hot springs discharge from The Geysers area, an average year around flow could be estimated at 5,000 gal/hr. The measurements of Allen and Day also show that the rate of ground water flow from the hot spring area varies with the season and they conclude, therefore, that part of the water from these springs is of local, near-surface origin.

No significant chloride content has been found in the hot spring waters, and the springs have been classified as the sodium bicarbonate type by White (1957, p. 1651).

History of development

The hot springs and steam vents of The Geysers were discovered in 1847, and the area became a nationally known spa in the latter half of the 19th century. Wells were first drilled for the purpose of generating electric power in 1921, and by 1925 eight wells were completed. Although sufficient steam was produced at that time to establish the feasibility of the project, there was no market for the steam and the project was abandoned.

In 1955, Magma Power Company obtained a 99-year lease on the hot spring areas located along the north side of Big Sulphur Creek. Between 1955 and 1957 Magma Power Company and its partner, Thermal Power Company, drilled six wells. On the basis of flow tests taken in December 1957, Pacific Gas and Electric Company was approached with the proposal that it construct a steam-electric power plant at The Geysers. On October 30, 1958, a contract between the producing companies and Pacific Gas and Electric Company was signed. Five more wells were drilled in the summer of 1959. In June 1960, a 12,500 kw generating plant went on stream utilizing approximately 250,000 lb/hr of steam supplied by four wells. Construction began in 1962 to increase the capacity of the plant to approximately 28,000 kw.

In 1960 and 1961 another well was drilled at The Geysers and two 2,000 foot wells were drilled in a thermal area located on Big Sulphur Creek a mile northwest of The Geysers. Although surface indication of heat flow are meager at this latter area, which is on the northwest end of the thermal spring zone, the two wells resulted in potentially commercial production of steam and further development is planned.

Production

The steam wells at The Geysers are drilled to depths of 500 to 1200 feet and are spaced at an average of 150 feet apart. For the wells drilled in 1957, 11¾-inch casing was set to depths ranging from 200 to 325 feet, cemented to the surface and then 8⅝-inch production casing was run to the bottom of the hole. The produc-

Photo 3. Drilling above the blowout in an attempt to seal permeable zone. *Photo by John Padan.*

tion casing was perforated at depths ranging between 460 and 700 feet. In the wells drilled during 1959, 13⅝-inch diameter holes were drilled below the surface casing and left uncased to the bottom. Total depths, casing depths and perforation intervals for 8 wells are shown in figure 4.

The wells were drilled with a modified diesel-powered rotary drill rig with depth capability of 2500 feet. Drill pipe consisted of 40-foot stands of 4½-inch A.P.I. pipe.

The major problem encountered in drilling the wells was the loss of drilling fluid into the steam-bearing fissures and the consequent danger of the uncontrolled escape of steam. Precautions taken against blowouts due to lost circulation included the availability of an adequate and dependable water supply for "quenching" the well, and an adequate supply of mud and filler material for sealing the borehole against leakage.

Because of the constant danger of blowouts, multiple blowout prevention equipment was used. A 12-inch valve was installed on the 13-inch casing, which is the last string. This valve remains on the well as part of the wellhead equipment. A spool piece is mounted above the valve, a Shaffer blowout preventer above that, and above this a rotating blowout preventer. The Shaffer blowout preventer contains two sets of rams, one designed to close on the drill pipe, the other to close on the drill collars.

The completed wellhead equipment includes a cyclone separator mounted horizontally on the discharge line. This separator removes fine rock particles that are produced with the steam.

In spite of these precautions, in 1957 a blowout occurred during the drilling of Thermal No. 4 well, and in the succeeding 5 years, all attempts to seal off the escape of steam have failed. This well was drilled on a flat bench about 100 feet back from a steep slope. While the well was being drilled, steam began to seep from the side of the bench below the wellhead. In a few days, the steam enlarged its own escape route until a crater was formed which measured approximately 5 or 6 feet in diameter. At first, an attempt was made to seal the blowout with filler materials, such as redwood bark, but the steam escaped with such a high velocity that the material was thrown from the crater. Next, surface rock material was bulldozed over the crater, but eventually this too was blown out and a new crater formed. In October 1959, a 550-foot well was directionally drilled to intersect Thermal No. 4 well below its connection with the blowout. This new well succeeded in diverting much of the escaping steam, but attempts to quench the blowout by pumping water down the directional well failed to stop the uncontrolled flow. In August 1962, a well was drilled directly adjacent to Thermal No. 4 in an attempt to seal the fracture zone with gravel and cement at a depth of about 300 feet (photo 3). Although this attempt was not successful in sealing off the blowout, it resulted in a slight increase of steam pressure in the adjacent wells.

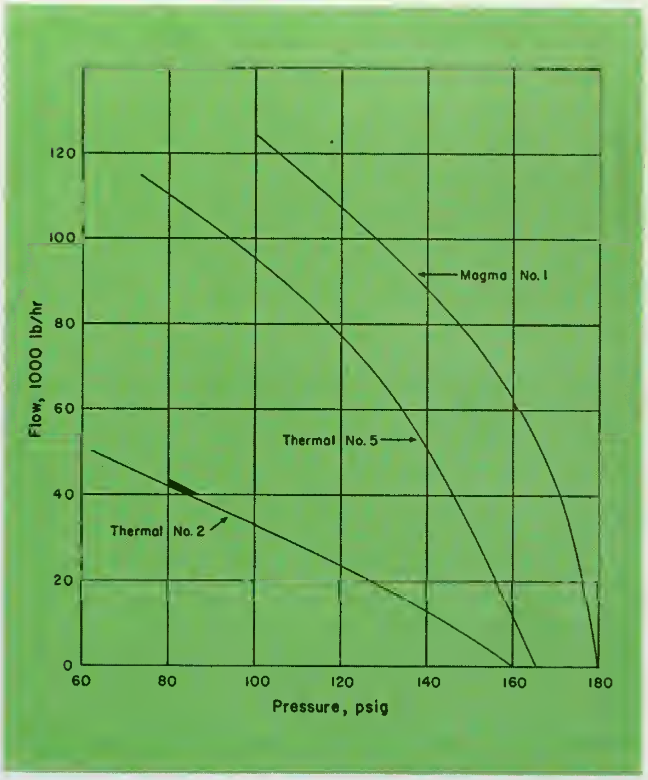


Figure 3. Mass flow-wellhead pressure curves for three Geysers wells. (After Bruce and Albritton, 1959.)

The quantity and pressure of steam flowing from the wells are determined by the size of the wellhead orifice which is controlled by a manually operated valve. Figure 3 shows the wellhead pressure-steam flow relationship for three representative wells. The wellhead temperature is in turn dependent upon the steam pressure. The following table shows representative wellhead pressures (in pounds per square inch, absolute) and corresponding temperatures of the effluent from Magma No. 1 and Thermal Nos. 2 and 5 measured in September 1958.

Pressure psia	*Temperature °C.*
59.7	169
62.4	171
75.4	181
94.2	184
104.1	181
132.1	188

Enthalpies calculated from these temperature and pressure data for the three wells are:

Well	*Enthalpy Btu per lb (referred to 32 F.)*
Magma No. 1	1207
Thermal No. 5	1199
Thermal No. 2	1204

Analyses of the steam from these three wells indicate that the percentage of non-condensable gases ranges from 0.68 percent to 0.83 percent by weight. A weighted average composition of the gases in the three wells is shown below (Bruce, 1961, p. 12).

Gas	*Volume percent at 60° F and 30″ Hg*	*Weight percent*
CO_2	69.32	88.73
CH_4	11.81	5.49
H_2	12.70	.74
$N_2 + A$	1.59	1.29
H_2S	2.99	2.96
NH_3	1.59	.79

Reservoir characteristics

On April 21 and 22, 1960, temperature logs were run by the Thermal Power Co. on 8 steam wells. These temperatures were taken with an iron-constantan thermocouple after the wells had been shut in for periods ranging between 1 hour and 2 months. The resulting temperature-depth curves for these wells are shown in figure 4. The static wellhead pressure recorded during the time of temperature meas-

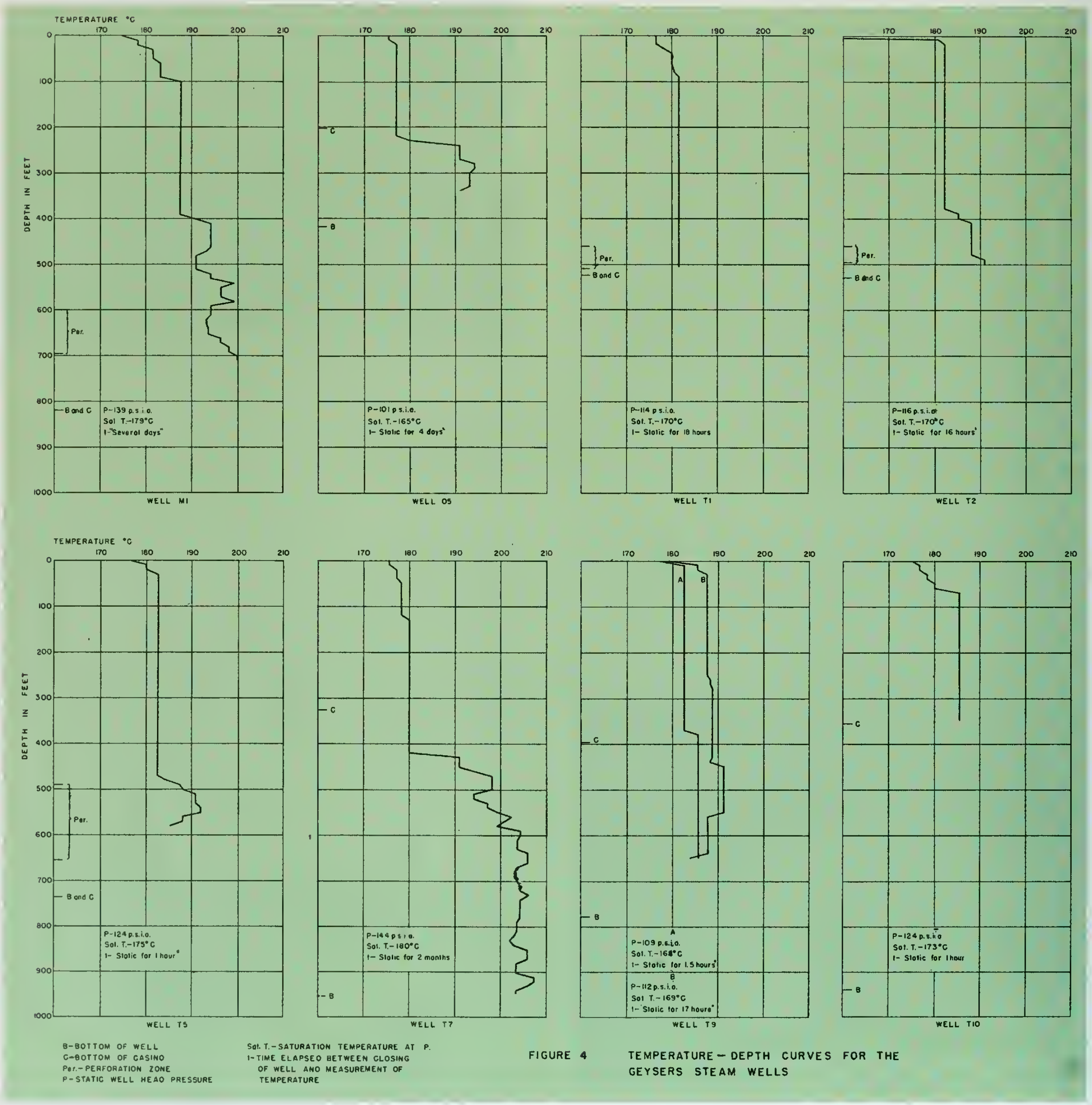


FIGURE 4 TEMPERATURE—DEPTH CURVES FOR THE GEYSERS STEAM WELLS

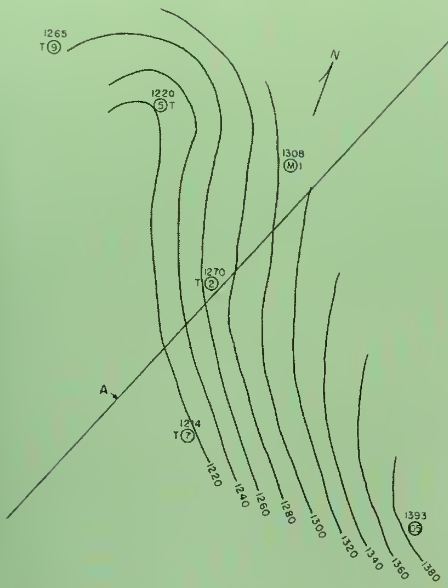


Figure 5. Contours drawn on bottom of constant temperature zone of The Geysers

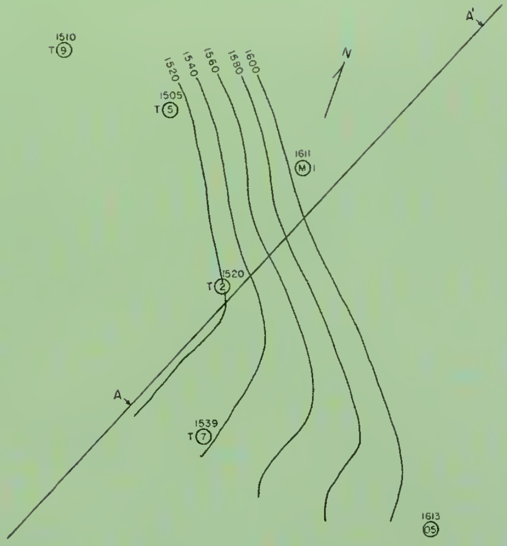


Figure 6. Contours drawn on top of ground water zone as defined by calculations described in text

Figure 7. Surface contours of The Geysers thermal area

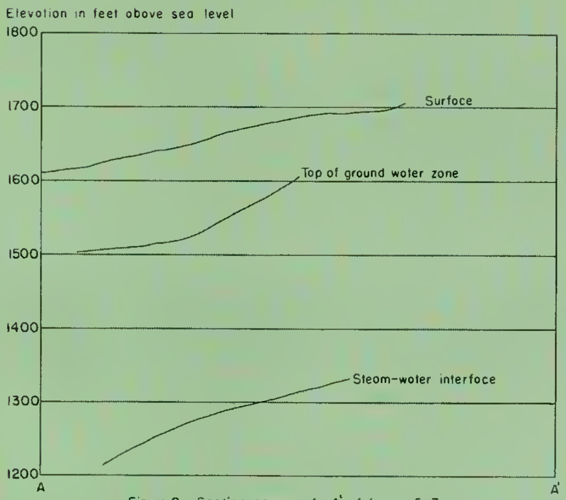


Figure 8. Section across A–A' of figures 5–7

0 100 200 300 Feet
Scale for figures 5–8

urement and the elapsed time between well shut-down and temperature measurement are indicated for each well.

A striking characteristic of these logs is the interval of constant temperature encountered in the upper part of the wells. In only one of the wells, T 7, does this constant temperature interval represent saturation conditions at the measured pressure. In all the other wells, the constant temperature shows various degrees of superheat, ranging from 8° C to 19° C, indicating that a liquid phase does not exist over the interval measured. There is a distinct temperature increase at the bottom of the constant temperature zone in six of the wells (figure 4). The maximum temperature below this temperature "break" is 207.5° C which was recorded in well No. T 7. It should be noted that the highest temperature measured in The Geysers steam field is approximately 300° C. This temperature was measured in 1957 at 600 feet in Magma No. 1 by the use of test-metals which melt at different temperatures.

The surface representing the bottom of this constant temperature zone is shown by contours in figure 5. Because geologic mapping indicates that steam is conducted through the dense, indurated graywacke of the Franciscan Formation by dipping fracture system (figure 2), it is not probable that the surface shown in figure 5, which dips only 25°, corresponds to one of these steam conducting fractures. Furthermore, this surface cannot be correlated with lithologic discontinuities disclosed by well cores and cuttings.

From the observations of Allen and Day (1927, p. 26-31) it is known that a body of ground water overlies the superheated steam zone. Therefore, it is suggested that the base of the constant temperature zone corresponds to a steam-water interface at the bottom of the body of ground water.

Immediately after closing a flowing well, a film of water should condense on the wall of the well where superheated vapor comes in contact with ground water or with the well casing, which is in contact with ground water. As heat is absorbed by the surrounding ground water, the temperature of the superheated vapor will decrease until saturation conditions for the pressure in the well pertain. At any time between the shut-down of the well and the final attainment of saturation conditions, the temperature in the part of the well that is in contact with ground water should not vary with depth. This is due to the fact that the temperature at which steam will condense on the wall of well is dependent on the steam pressure, which, under static conditions, would be essentially constant with depth. The validity of this proposed explanation for the constant temperature zone is supported by the fact that the only well in which saturation conditions exist in the constant temperature interval is well No. T 7. This well had been closed for the longest period of time before the temperatures were measured, suggesting that all the wells would eventually reach saturation conditions within the depth interval of constant temperature.

If the steam is not confined in the reservoir by overlying impermeable beds, then a hydrostatic equilibrium must exist between the nearsurface ground water body and the steam reservoir, i.e., the expansive pressure of the steam must equal the hydrostatic pressure of the water body which confines it. Therefore, from the static wellhead pressure it should be possible to compute the height of the overlying water body at the point at which the well is drilled. This hypothesis has been tested by calculating the height of a column of water which would produce the static wellhead pressure given in figure 4, and adding its height to the elevation of the temperature "break" at the bottom of the constant temperature interval. The surface thus defined, contoured in figure 6, should represent the top of the ground water body overlying the steam. Two features of the surface defined in this manner support the validity of these calculations: a) there is a general similarity in configuration between the topography of The Geysers area (figure 7) and the configuration of the upper boundary of the proposed ground water body (figure 6), thus indicating a relationship which would be expected between the two surfaces; b) the elevation of the surface shown in figure 6 ranges between 1500 and 1600 feet, which corresponds to the range in elevation of the principal natural springs in Geyser Canyon.

Figure 8 is a cross-section through The Geysers area illustrating the spatial relationship between the ground surface, the top of the ground water body, and the steam-water interface, as defined by the method described above.

Although the static pressure of the steam is dependent upon the hydrostatic head above the steam, the height of this water column is principally determined by the rate of heat flow into and out of the overlying water body. This water body is a mixture of meteoric water, originating in the immediate vicinity of The Geysers, and condensed steam from below. Under natural conditions, heat is released from this groundwater body by flow of hot water from the springs in Geyser Canyon and the rate of this water flow is determined by the permeability of the fracture zone. Evaporation of water must also be an important cause of heat loss because water in the ground water body is at, or very near, its boiling point throughout its pressure range. The rate of heat loss from the ground water body must be equal to the rate at which heat is supplied at the steam-water interface. If the rate of heat flow into the water body were greater than the rate of heat loss, the water would "boil away" and superheated steam would escape directly to the surface. If the rate of flow of cold meteoric water into the ground water body increased, the rate of heat flow into the water body by steam condensation would also increase because of the necessity of raising a greater volume of water to its boiling point. Eventually the rate of heat flow into the area would be limited by the physical dimensions of the feeding fractures, and, on continued inflow of cold meteoric water, a superheated steam phase could no longer exist in the system.

The balance of heat flow into and out of the ground water body, as described above, is responsible for maintaining the density inversion of the two phases in the system. Under static conditions, it would not be possible for a steam phase to be in mechanical equilibrium with an overlying liquid phase due to their difference in density. Because the movement of both phases through the system is determined not only by density differences, but also by the thermodynamic equilibrium existing between the two phases in an open and flowing system, such a density inversion is made possible.

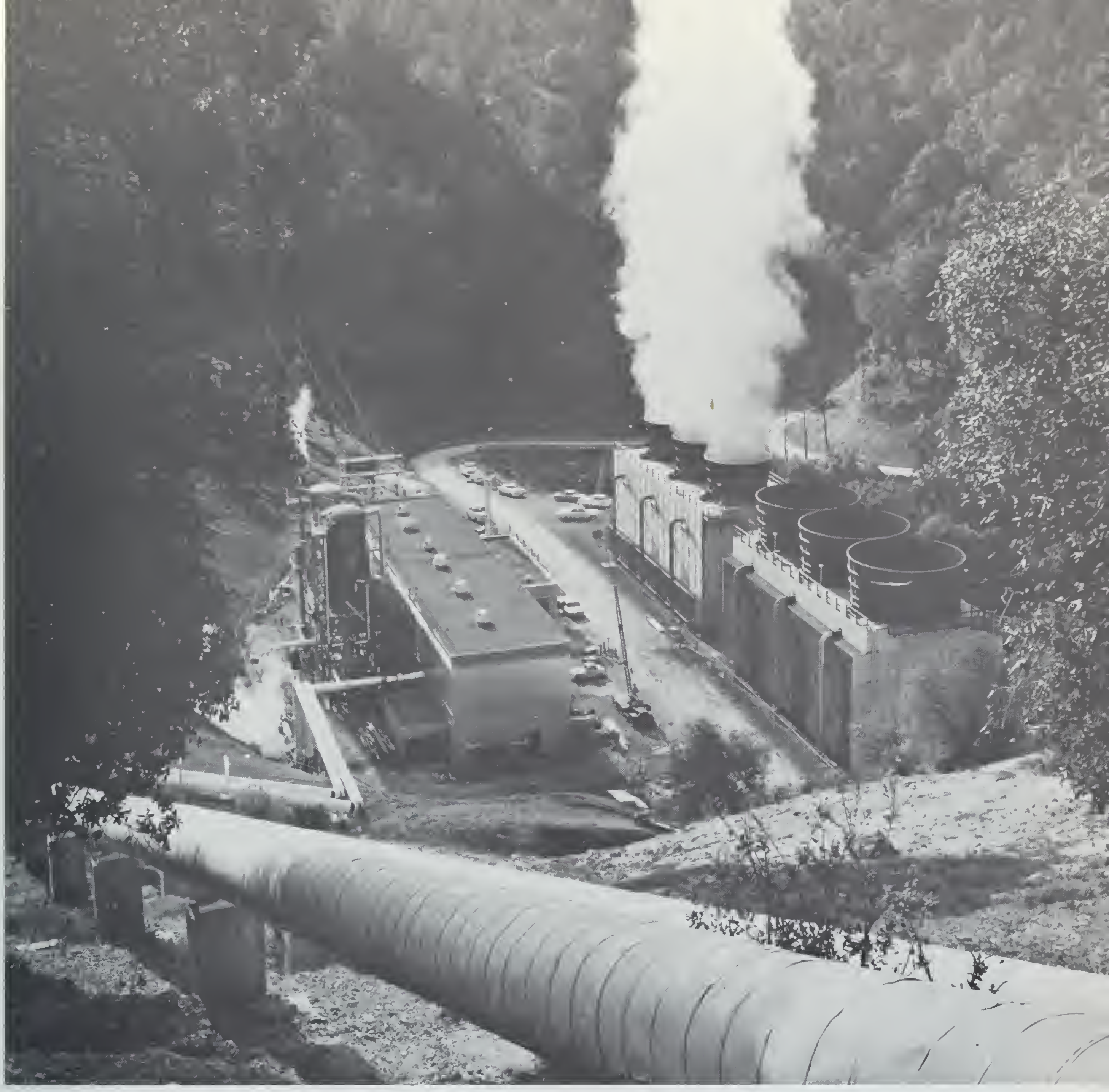


Photo 4.
Power generating station
and condensing units at The Geysers.
Photo courtesy Pacific Gas and Electric Company.

The rate at which steam is condensed in the ground water body under natural conditions can be estimated in the following manner. The natural thermal spring water, which is derived from the ground water body, is a mixture of meteoric water and steam condensate. The enthalpy of the meteoric water is approximately 20 cal/gm and the enthalpy of the steam is 667 cal/gm. Mixing of these two waters results in a water body having an enthalpy of approximately 100 cal/gm. Water is released from this body at the approximate rate of 5,000 gal/hr. If x is the percentage of condensed steam in the natural spring flow, then the following equation expresses the above conditions:

$$667x + 20\,(1 - x) = 100, \text{ and } x = 11.6\%$$

Therefore, under natural conditions, approximately 1.3 lb. of steam is condensed in one second. At the average enthalpy of 667 cal/gm, this estimated steam flow gives an estimated natural heat flow from The Geysers thermal area of 4.1×10^5 cal/sec. This figure, however, does not include heat loss by evaporation from the ground water body or radiation of heat to the atmosphere.

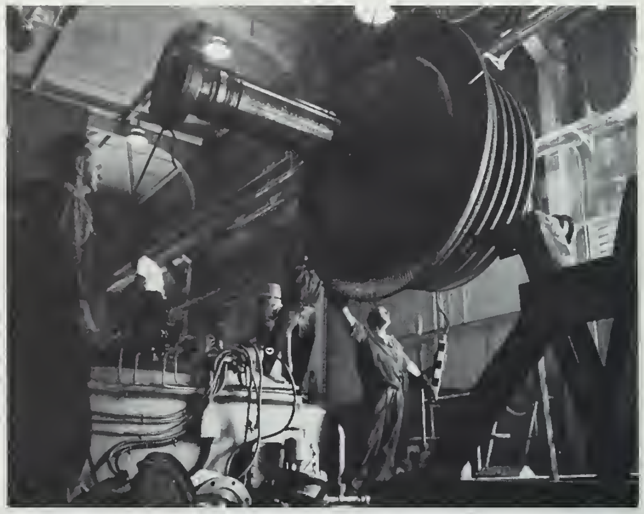


Photo 5. Turbine blades being removed for annual cleanup, The Geysers Power Plant. *Photo courtesy Pacific Gas and Electric Company.*

An estimated limit for the maximum rate of mass flow through the steam wells at The Geysers is 600,000 lb/hr. Water loss from natural spring flow (approxi-

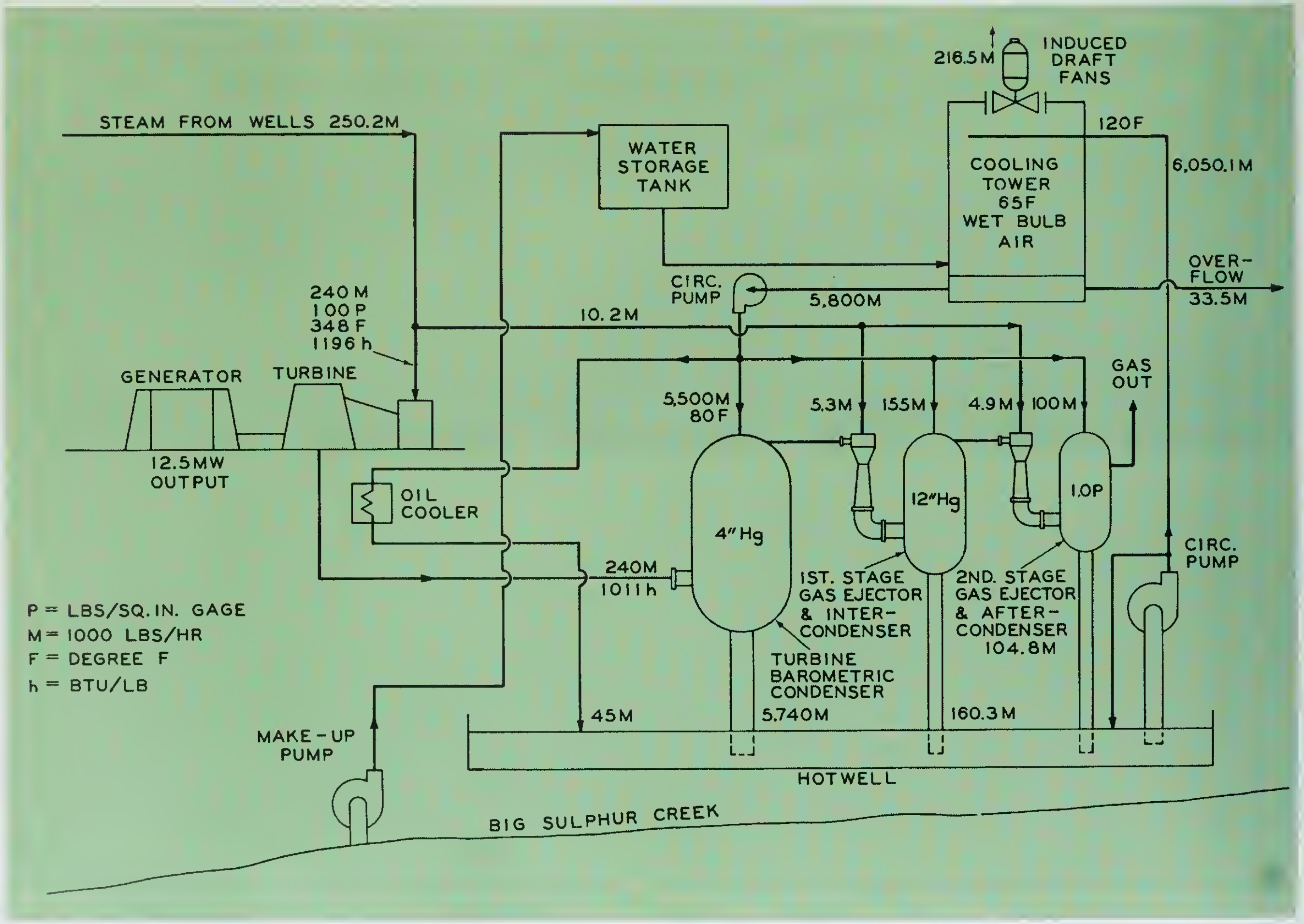


Figure 9. Flow diagram of steam cycle in The Geysers power plant. (After Bruce and Albritton, 1959.)

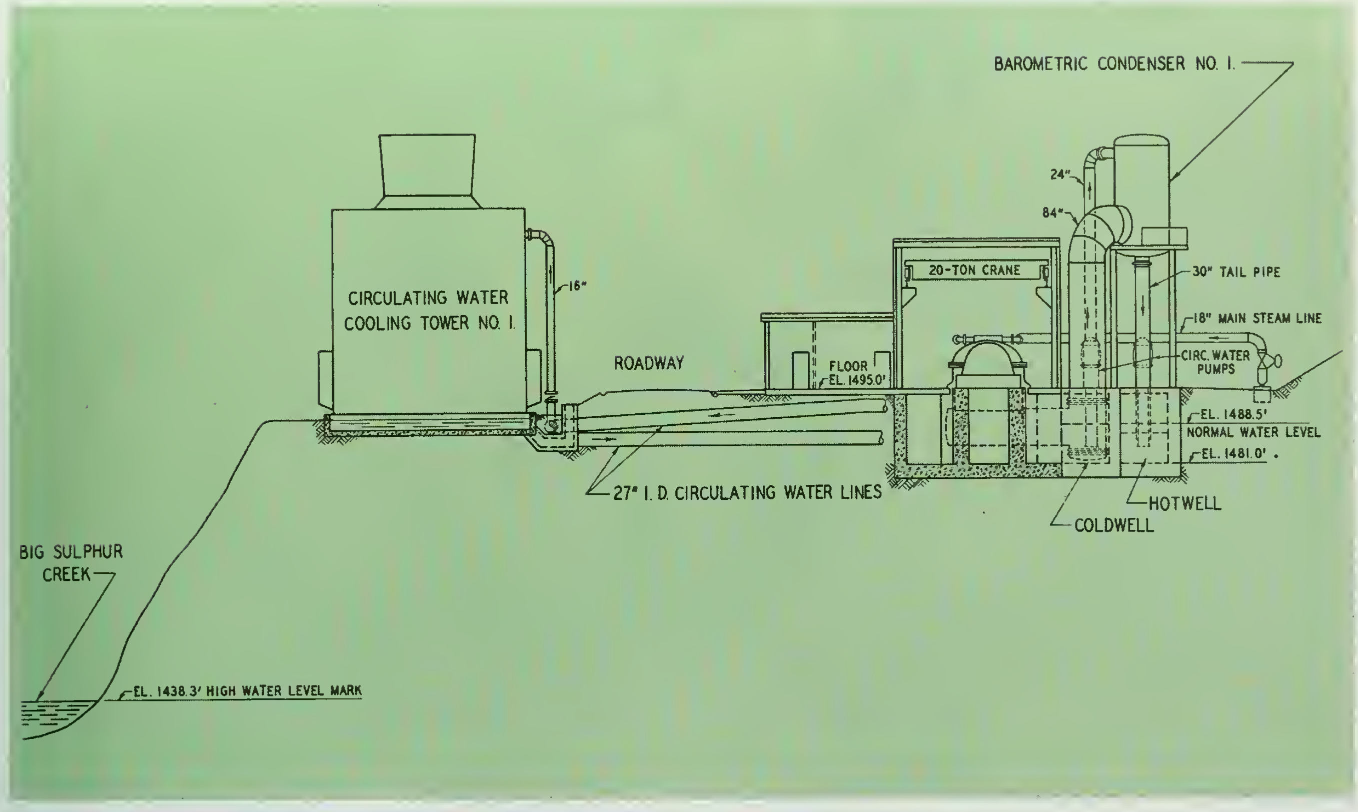


Figure 10. Distribution of units in The Geysers power plant. (After Bruce and Albritton, 1959.)

mately 40,000 lb/hr), from evaporation, and from the uncontrolled "blowout", however, are not included in this figure. If these other factors are considered, a conservative estimate for maximum possible total steam flow from the area would be about 800,000 lb/hr. At an average enthalpy of 667 cal/gm, this estimated steam flow gives a maximum estimated heat flow of 6.7×10^7 cal/sec. Comparing this figure with the calculated natural heat flow shows that drilling the wells made it possible to increase the rate of heat flow from the thermal area by approximately 170 times the rate of natural heat flow.

Utilization

The steam produced at The Geysers has a comparatively low content of non-condensable gases, and it is superheated. Because of the low non-condensable gas content, elaborate gas removal equipment is not necessary in order to achieve a low back pressure behind the turbine; and because the steam is dry, it can be fed directly into the turbine without first passing through water separating tanks (as is necessary in most other steam producing areas).

The flow diagram for the steam cycle is shown in figure 9, and an elevation of the plant, illustrating the distribution of the units, is shown in figure 10. The turbine is designed for 100 psig (pounds per square

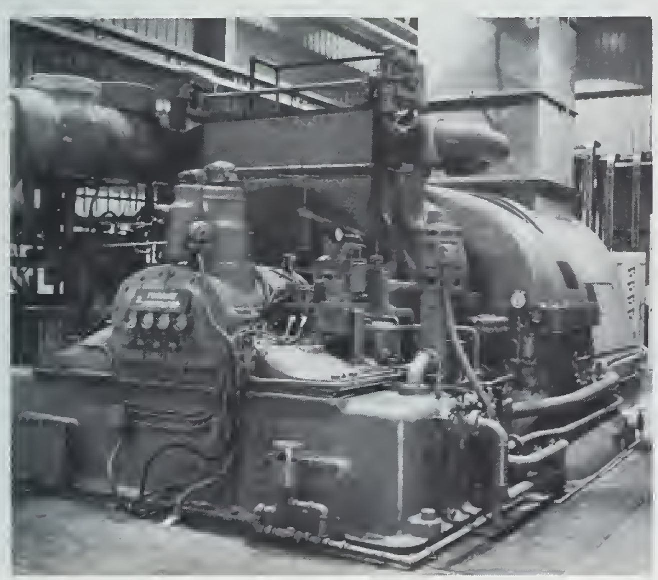
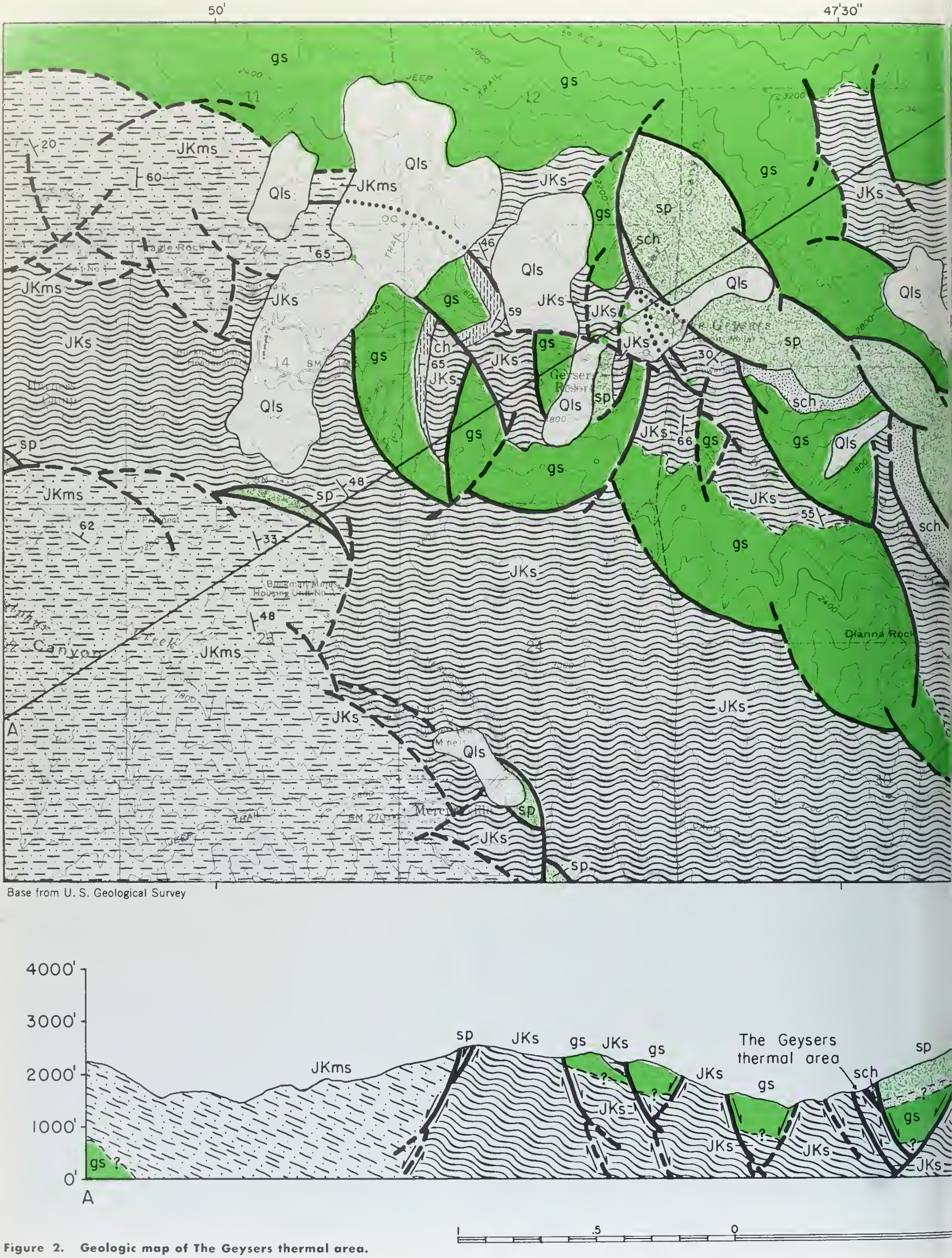
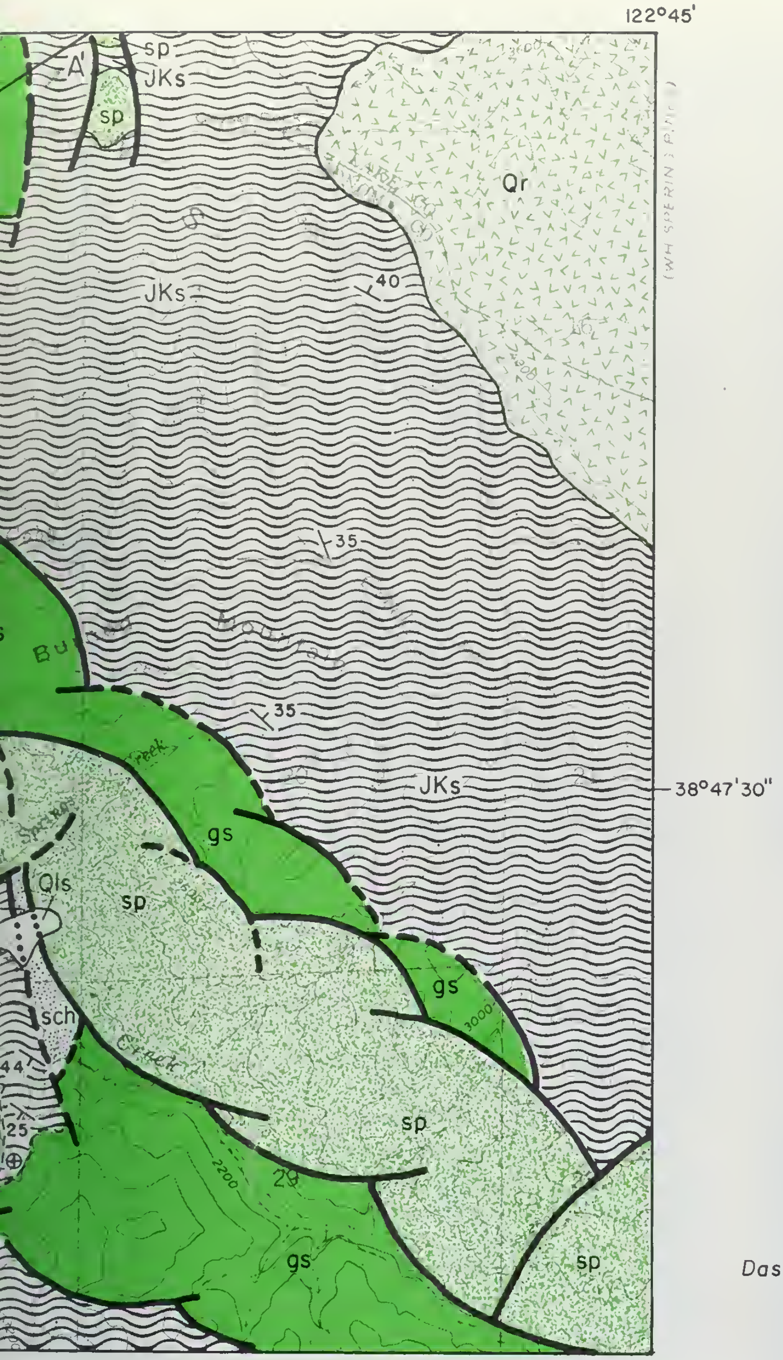


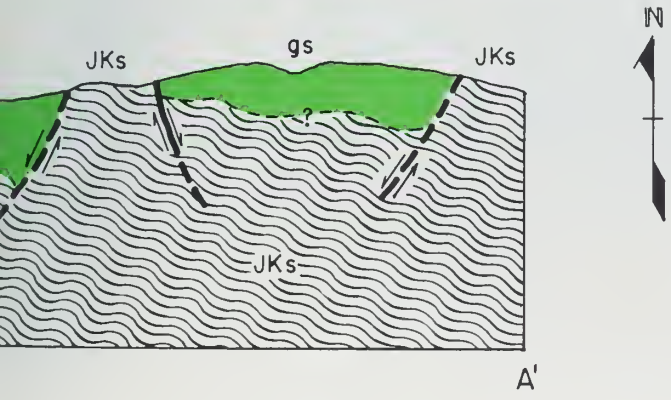
Photo 6. One of the two turbine generator units at The Geysers power plant. *Photo courtesy Pacific Gas and Electric Company.*



Base from U. S. Geological Survey

Figure 2. Geologic map of The Geysers thermal area.





EXPLANATION

QUATERNARY	Qls	Landslide
	Qr	Rhyolite flows and tuffs
JURASSIC—CRETACEOUS	JKms	Micaceous graywacke; shale
	sch	Amphibole schist
	sp	Serpentine
	ch	Chert
	gs	Greenstone
	JKs	Graywacke and shale

Contact
Dashed where approximately located

Fault (down on concave side)
Dashed where approximately located

Concealed fault

⊥
Strike and dip of beds

⊕
Horizontal beds

Hot spring

Steam well

inch, gauge) and 348° F inlet steam conditions and a back pressure of 4 inches Hg.

Because there is no boiler, it is not necessary to recycle the steam condensate through the turbine and a barometric condenser is used in order to achieve the low back pressure. This type of condenser is one in which the cooling water is sprayed directly into the exhaust steam. Because less water is lost by evaporation than is supplied by the condensed steam, no external make-up water is required except to fill the cooling system initially. The amount that overflows from the cooling tower is 12 percent to 40 percent of the steam condensate depending on the atmospheric conditions. The use of this condensing system provides about twice the electrical output per pound of steam compared with one which exhausts to the atmosphere.

Approximately 240,000 lbs of steam per hour is supplied from four of the wells to the turbine through a 2,000-foot line, 20 inches in diameter. An 84-inch diameter duct carries the exhaust steam from the turbine to the barometric condenser. The non-condensable gases are removed at the top of the condenser by a two-stage steam jet gas ejector.

The condenser vessel is mounted vertically 28 feet above ground level, in order to allow room for a 34-foot long, 30-inch diameter barometric leg which is connected to the bottom of the condenser. The mixture of cooling water and condensate falls down to the hotwell in which the lower end of the barometric leg is immersed, thus maintaining a seal for the vacuum. The flow of circulating water through the hotwell is about 12,000 gallons per minute.

From the hotwell, the condensate is cycled to the cooling tower, and then back to the condenser. The cooling tower is a three cell induced draft type, designed to cool 12,000 gallons per minute of water from 120°F to 80°F with a wet bulb air temperature of 65°F.

The alternating current generator is rated 12,500 kva, 1,000 rpm, 3 phase, 60 cycle and 11.5 kv. The current is stepped up to 60 kv for transmission over a new 10-mile line to the existing Fulton-Hopland transmission circuits.

Because of the sulfur content of the thermal fluid, intensive tests were made to study the corrosiveness of the steam condensate and circulating water. These tests showed that the main steam line could be made of carbon steel pipe, but it was necessary to use type 304 (18 percent chrome, 8 percent nickel) stainless steel pipe for the condensate lines. Type 304 stainless steel plate is used for the exhaust pipe from the turbine, and Type 316 (18 percent chrome, 14 percent nickel, 2½ percent molybdenum) stainless steel is used in the barometric condenser.

The structural parts of the cooling tower are made of redwood, and the fill made of styrene plastic. All nails, fasteners and bolts are of Type 303 or 204 stainless steel and all cast iron fittings are coated with a baked phenolic coating. Cement asbestos board is used to enclose the tower.

Economics

On the basis of feasibility and economic studies, Pacific Gas and Electric Co. signed a contract on October 30, 1958 which provided that the first unit constructed by P.G. & E. would be 12,500 kw and a second unit would be at least equal in size if warranted by the supply of steam. P.G. & E. would pay for the steam at a rate of 2.5 mills per net kwh of electric energy delivered to the transmission line for the first two units and an escalated price for energy from any additional units (Bruce, 1961, p. 5). During 1961, the gross income to Magma and Thermal Power Companies for the sale of steam was approximately $250,000.

A capital cost of $40 to $60 per foot of completed steam well has been estimated (English, 1961, p. 12). This cost includes such items as roadways, cellars, warehousing, geologic studies, well testing, wellhead equipment, casing and administration.

The cost of the first 12,500 kw generating plant plus the 11.5/60 kv step-up switchyard was approximately $1,900,000. A second-hand turbine generator was used in this unit, and if it had been necessary to supply a new unit about $500,000 would have been added to the plant cost. The 10-mile 60 kv transmission line cost is about $220,000 (Bruce, 1961, p. 5).

The technical and economic success of The Geysers geothermal power plant is well established. In April 1962, construction began on a second generating unit which will raise the plant's capacity to approximately 28,000 kw. The new design pressure will be 80 psig for the first (original) unit and 65 psig for the second unit. Steam from the thermal field will be supplied to the two units at the rate of approximately 550,000 lb/hr.

CASA DIABLO

Casa Diablo Hot Springs are located in Mono County, about 40 miles northwest of Bishop on Highway 395. These springs are one of several hot spring groups on the west side of Long Valley, near the headwaters of the Owens River. Long Valley occupies the east side of a large topographic basin which is oval in shape and oriented with its long axis east-west. This basin is known as the Mammoth Embayment because of the east-west offset which it produces in the steep, northeast front of the Sierra Nevada. Mono basin, a similar topographic depression, is located about 10 miles north of the Long Valley area.

Geology

The Sierra Nevada on the west and south of Long Valley, and the Benton Range and the Black Mountains on the east of the basin, are composed of Late Paleozoic metasedimentary rock which is intruded by Cretaceous rocks ranging in composition from gabbro to granite (Rinehart and Ross, 1956, p. 5-7). Cenozoic volcanic rocks, as well as alluvial and glacial deposits, fill the Long Valley basin and cover much of the pre-Tertiary rocks to the north.

The gravity data shown in figure 11 indicate that Long Valley is a structural depression as well as a physiographic basin, and is bounded on all sides by steep faults. The structural depression is also elliptical in shape, 23 miles long and 12 miles wide. The Cenozoic deposits in the depression increase gradually from a thickness of less than 5,000 feet on the west to 18,000±5,000 feet on the east (Pakiser, 1961, p. 253). Pakiser has interpreted Long Valley to be "a volcano-tectonic depression caused by subsidence along faults, following extrusion of magma from a chamber at depth".

Gilbert (1938, p. 1860) believes that the Long Valley depression was the major locus for vents which erupted the Pleistocene Bishop Tuff, a pyroclastic deposit of the nuée ardente type. The visible extent of the Bishop Tuff is approximately 350 square miles, but because of its probable continuation beneath the alluvium of Owens, Long and Adobe Valleys, the total areal extent of the tuff should be about 400 to 450 square miles. The thickness of the tuff exposed in stream gorges ranges between 400 and 500 feet; consequently, the total volume of the Bishop Tuff approximates 35 cubic miles (Gilbert, 1938, p. 1833).

Approximately 200 feet of Pleistocene lacustrine deposits (Cleveland, 1961) overlying rhyolite flows in

Photo 7.
East end of Long Valley structural depression.
Photo by Mary Hill.

Photo 8.
Creek flowing through rhyolite near Casa Diablo, Mono County.
Photo by Mary Hill.

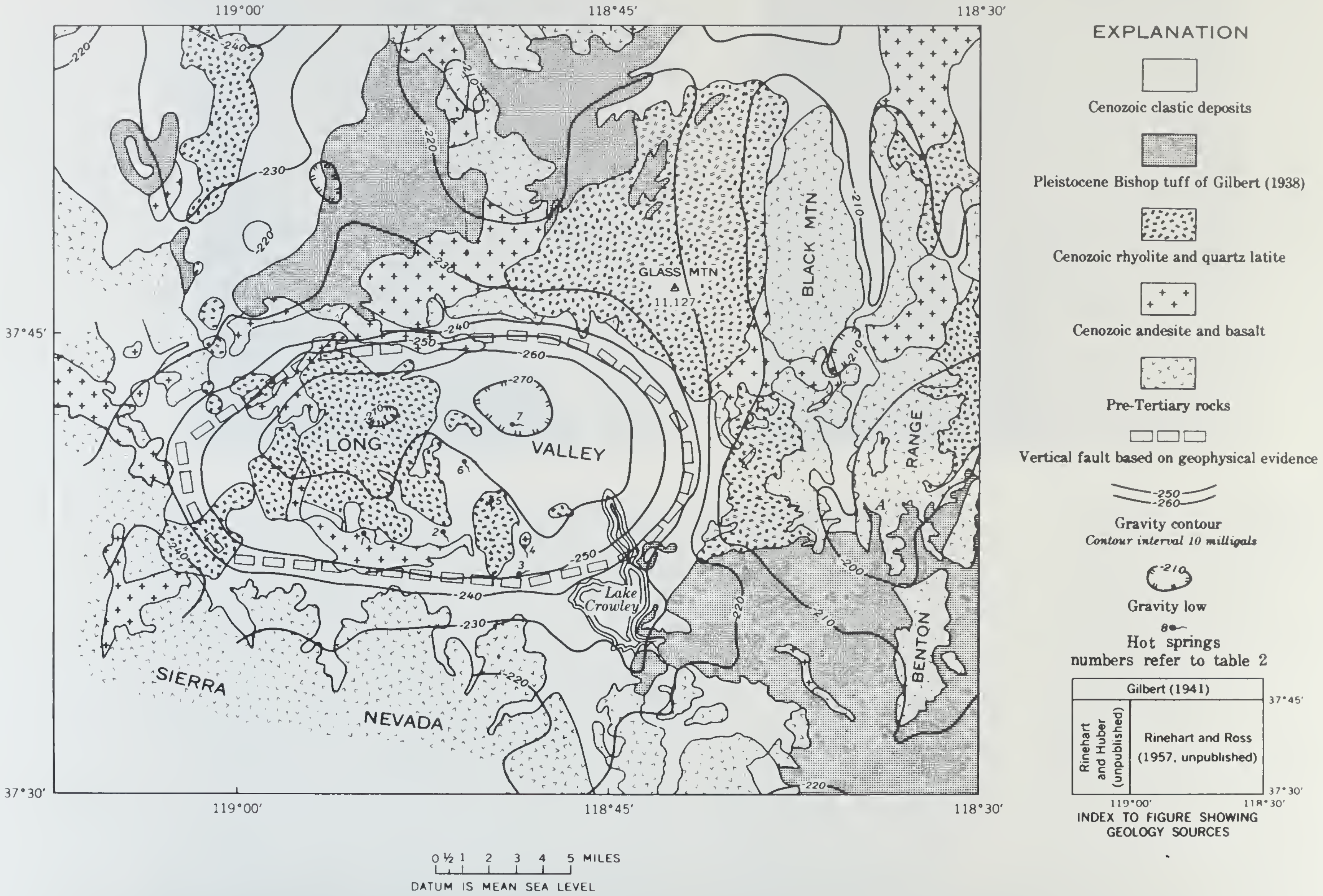


Figure 11. Geologic and gravity anomaly map of Long Valley. (Gravity data after Pakiser, 1961.)

Long Valley is evidence that the depression has existed at least from mid-Pleistocene. Volcanic activity in this region has continued to a very recent time, as indicated by the presence of a basalt flow in the Mammoth Creek area which overlies lacustrine sediments thought to be deposited during the Tahoe glaciation (Cleveland, in press).

An aeromagnetic survey of the region disclosed a sharp magnetic high, having a relief of from 2500 to 5000 gammas, located over the center of Long Valley (Pakiser, 1961, p. 252). This magnetic anomaly roughly corresponds to a local positive gravity anomaly which has a relief of about 10 milligals, as compared with a 60 milligal negative anomaly over the major part of the Long Valley depression. The calculated depth to the upper surface of the magnetic body is about 3000 feet below the valley floor, which places the top of the body in the upper part of the Cenozoic section as determined by gravity methods. This mass of dense and magnetic material may represent the buried volcanic or intrusive rock which is the heat source for the various thermal springs in Long Valley.

The principal drilling in this area for geothermal power has been done at Casa Diablo Hot Springs. The springs are located near two structural features: a) a fault trending north-northwest, and b) a west-trending contact between a Quaternary basalt flow and a late Tertiary rhyolite (Rinehart and Ross, in press). The rhyolite is the principal flow covering the west half of the Long Valley depression. Because of poor outcrops in the Casa Diablo Hot Springs area, the nature of the basalt-rhyolite contact is not known with certainty.

Photo 9.
Extent of thermal activity prior to drilling of steam wells at Casa Diablo Hot Springs. ***Photo by Mary Hill.***

Rinehart and Ross (written communication, 1962) are of the opinion that the thermal activity at Casa Diablo Hot Springs, as well as in most of the Long Valley area, appears to be localized along steeply dipping to vertical faults that trend north to northwest. The writer believes that arcuate faults, trending to the northwest from Casa Diablo Hot Springs are suggested by the configuration of the contact between the Tertiary rhyolite and younger Pleistocene units. Moreover, inspection of aerial photographs strongly suggests that collapse structures enclosed by arcuate faults are common in the Long Valley depression. If this is correct, then there is a striking similiarity between the geologic structure of the Casa Diablo thermal area and the graben structure at The Geysers in Sonoma County.

Thermal activity

The surface temperature and approximate discharge of seven spring groups in Long Valley are given in table 2 (Stearns, Stearns, and Waring 1935, p. 126-127). The number given to each spring group corresponds to the number in figure 11.

In addition to these thermal areas, there are many localities, mainly northeast of Casa Diablo, where the rhyolite has been altered to clay and opal by hydrothermal solutions. Although there is evidence for very recent thermal activity at a few of these clay deposits, it is believed that most of them formed in the mid-Pleistocene and are not closely related to present thermal activity (Cleveland, in press).

Table 2. Temperature and discharge of Long Valley thermal springs (after Stearns, Stearns and Waring, 1935, p. 126-127).

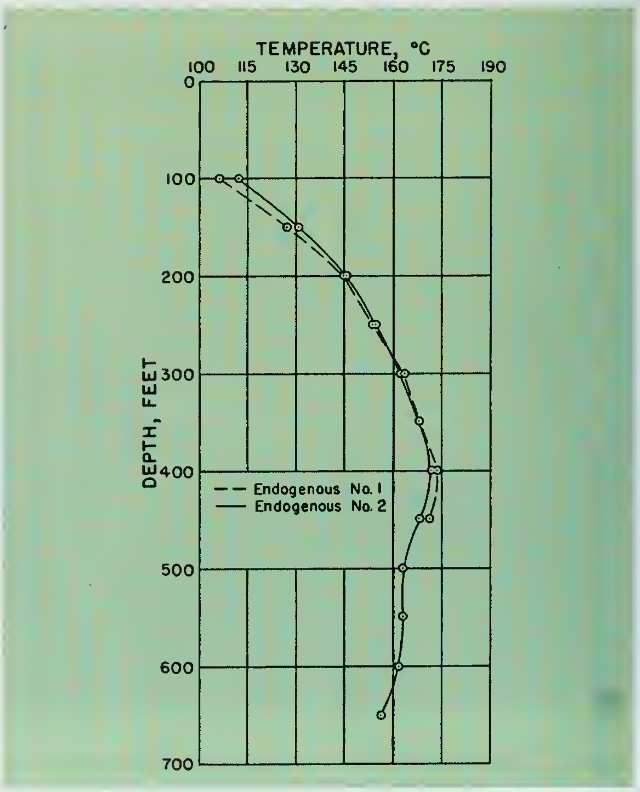
Map no.	Location	Name	Temp. °C	Total discharge, gal/min	No. of springs
1	NW¼, sec. 32, T.3S., R.28E.	Casa Diablo Hot Springs	46-90	35	20
2	NW¼, sec. 35, T.3S., R.28E.	Casa Diablo Hot Pool	82	Intermittent	--
3	NW¼, sec. 6, T.4S., R.29E.	Whitmore Hot Springs	36	306	2
4	NE¼, sec. 31 T.3S., R.29E.	--	23-38	450	4
5	NE¼, sec. 30, T.3S., R.29E.	"The Geysers"	49-94	500	5
6	NW¼, sec. 13, T.3S., R.28E.	--	77	5	1
7	NE¼, sec. 7, T.3S., R.29E.	--	--	--	--

Photo 10.
Geologist taking temperature of Casa Diablo Hot Pool. *Photo by Mary Hill.*

History of development

In 1959, two wells were drilled at Casa Diablo Hot Springs by the Magma Power Company. The first well, Mammoth No. 1, was drilled about 1200 feet northeast of Highway 395 and the second just west of the highway near an active fumarole. Mammoth No. 1 was drilled to 1,063 feet, but the second well was abandoned at a shallow depth because extensive steam seeping around the well area indicated very pervious ground. In 1960 Magma Power Co. entered into a partnership agreement with Endogenous Power Co. (now known as Natural Steam Corporation). This new company drilled the third, fourth and fifth wells on the west side of the highway, approximately 100 yards apart in a northwest-southeast line. From south to north these wells are named Endogenous No. 1 through 3, and were drilled to 630, 810 and 570 feet, respectively. In 1961 Endogenous No. 4 was drilled adjacent to the other Endogenous wells, but east of the highway. Also in 1961, Endogenous Power Co. drilled Chance No. 1 at Casa Diablo Hot Pool, a thermal spring 3 miles east of Casa Diablo. In 1962, Endogenous Nos. 5, 6, and 7 were drilled at Casa Diablo on the east side of Highway 395 to 405, 756 and 670 feet, respectively.

Figure 12. Thermal gradient of Endogenous Nos. 1 and 2, Casa Diablo thermal area.



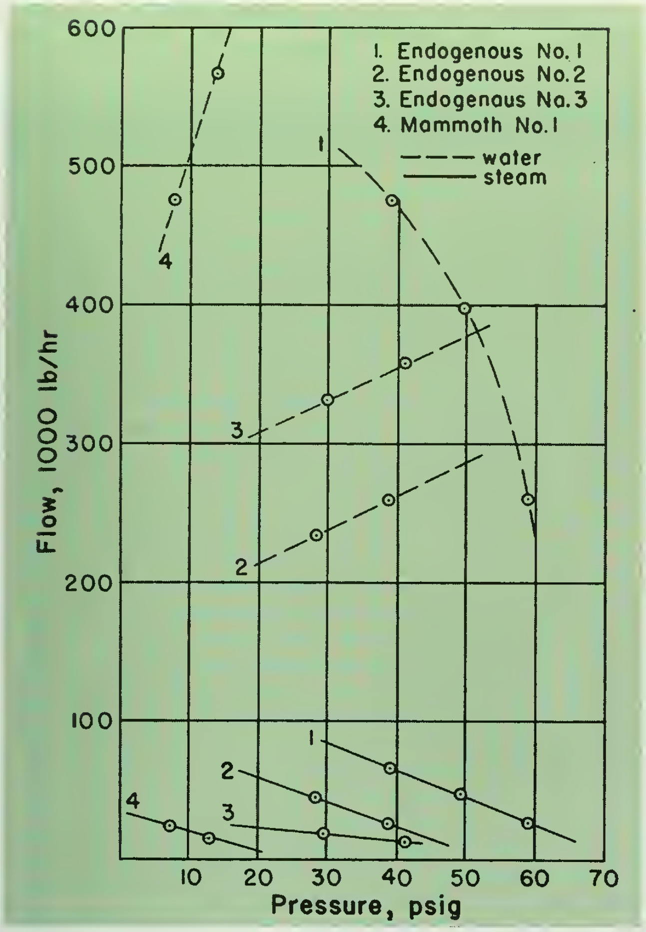


Figure 13. Mass flow-wellhead pressure curves for Casa Diablo steam wells.

Production

The four wells tested to date are Endogenous No. 1 through No. 3 and Mammoth No. 1. The Endogenous wells were completed with two strings of casing, leaving an open hole below. The outer casing is 13⅜ inches in outside diameter and was set to depths ranging from 140 to 220 feet. The inside casing is 9⅝ inches in outside diameter and was installed to depths ranging between 350 to 400 feet. Both sets of casings are hung from the surface and cemented from bottom to top. Mammoth No. 1 has one string of casing 165 feet long and 9⅝ inches in outside diameter.

Temperatures in the wells were taken with a maximum recording thermometer after the wells had been static for several weeks. Under these conditions, the maximum temperatures recorded in Endogenous No. 1 through 3 were 178° C, 174° C and 172° C, respectively, and 148° C in Mammoth No. 1. Figure 12 shows the thermal gradients measured in Endogenous Nos. 1 and 2 after the wells had been static for a period of six months. The temperatures shown in figure 12 were measured with a mechanical temperature logging device in the latter part of 1962. This device was developed in New Zealand and is considered more reliable than electrical instruments for recording well temperatures under these extreme conditions.

The four wells produce a mixture of saturated steam and hot water. Well performance was tested by W. M. Middleton in October 1960. The following table summarizes the well characteristics under producing conditions.

Well no.	*Temperature* °*C*	*Pressure psig*	*Steam lb/hr*	*Water lb/hr*
Endogenous No. 1	148	39	69,300	473,000
Endogenous No. 2	181	38.5	45,000	233,500
Endogenous No. 3	157	30	19,000	330,000
Mammoth No. 1	132	7.5	25,000	471,000

The chemical constituents in water and condensate from the Casa Diablo wells are given in table 3.

The steam produced from Endogenous No. 4 contains 0.36 percent by volume and 0.87 percent by weight of non-condensable gases. This gas is composed of 98.25 percent by volume or 98.64 percent by weight of CO_2 and 1.75 percent by volume or 1.36 percent by weight of H_2S. An infrared spectrum of the samples indicated that there were no other gases present.

Reservoir characteristics

The variation of steam and water flow with wellhead pressure for the four wells is shown in figure 13. As would be expected, steam flow increases with decreasing pressure in all the wells. In Endogenous No. 1, water flow increases with decreasing pressure, but in the other three wells, water flow decreases with decreasing pressure. The anomalous relationship of

Table 3. Chemical constituents of fluids from Casa Diablo wells in ppm.

	Endogenous No. 1[2]	Endogenous No. 1[1]	Endogenous No. 2[2]	Mammoth No. 1[1]	Endogenous No. 4[3]	Endogenous No. 4[4]
SiO_2	250	278	256	292	200	0.8
Ca		2		30	4	
Mg		tr.		tr.		
Na	380	236	375	247	308	5
K	47	62	45	71	32	
Li		4		3	0.3	
Fe		5		4		
Al		2		1		
B		60		49	11	0.3
Cl	276	266	276	301	227	5
SO_4	61	108	62	124	96	2
H_2S					14	11
F					20	
NH_3					0.1	0.5
CO_2					180	205
As					0.2	
pH	8.86	7.5	8.61	8.0	6.5	4.9

Analyst: Abbot A. Hanks, Inc., San Francisco.

[1] Sample taken from wellhead immediately after flowing. Some water flashed to steam.

[2] Sample taken from wellhead after cooling. No flashing to steam.

[3] Water sample taken during flow test.

[4] Condensate of steam sample taken during flow test.

decreasing water flow with decreasing wellhead pressure is probably the effect of relative permeability. When both a vapor and liquid phase are being produced, a reservoir is considerably more permeable to the vapor than to the liquid. At low wellhead pressures, vapor expansion in a reservoir could be so great as to block the passages to liquid flow. The effect of relative permeability becomes more pronounced as the absolute permeability of the rock decreases.

The relative permeability effect should not be noticeable where water is flashing to steam within the well bore, provided that the bore has not been restricted by mineral deposition. If on the other hand, some water flashes within the reservoir rock, the relative permeability effect should become more pronounced. Where flashing occurs within the reservoir rock, the relative permeability effect offers a method for comparing reservoir permeability from one bore to another, irrespective of the area of the hole open to production: the greater the tendency of a water production curve to flatten or even to slope in a positive direction (figure 13) with decreasing wellhead pressure, the less permeable the reservoir in the vicinity of the well displaying this type of water production curve.

In regard to the four Casa Diablo wells, the water production curve of Endogenous No. 1 reflects the greatest reservoir permeability, Mammoth No. 1 the least permeability, and Endogenous No. 1 and 2 intermediate permeability. The comparatively large total flow of Mammoth No. 1 is most probably due to the fact that its "open hole area" is approximately three times greater than that of any of the other wells. The comparatively low permeability reflected by the production curves of Endogenous No. 1 and 2 and Mammoth No. 1 may be due to either or both of two factors: (a) the well flow is restricted by the deposition of calcite and silica in the region where hot water is flashing to steam, or (b) these three wells did not intersect the main steam bearing fissure, but are producing from relatively small subsidiary fractures. In order to explain the differences of steam production as well as the slope of the water production curve between Endogenous No. 1 and Mammoth No. 1, the latter interpretation is preferred, because both bores were cleaned of calcite deposits before the tests were made. On the other hand, Endogenous No. 1 and 2 seemed to sustain equal mass flows directly after completion of the wells, so that calcite deposition in Endogenous No. 2 is the more probable explanation of its relatively low rate of flow.

SASSO, ITALY, 1850.

SALTON SEA

The Salton Sea thermal area is located in Imperial County approximately 3 miles southwest of Niland and at the southeast end of the Salton Sea. Although little development work has been done on this area as compared to the Geysers steam field, the future of the field is very promising because of the high heat flows measured in exploratory wells and because of the large implied area of the field.

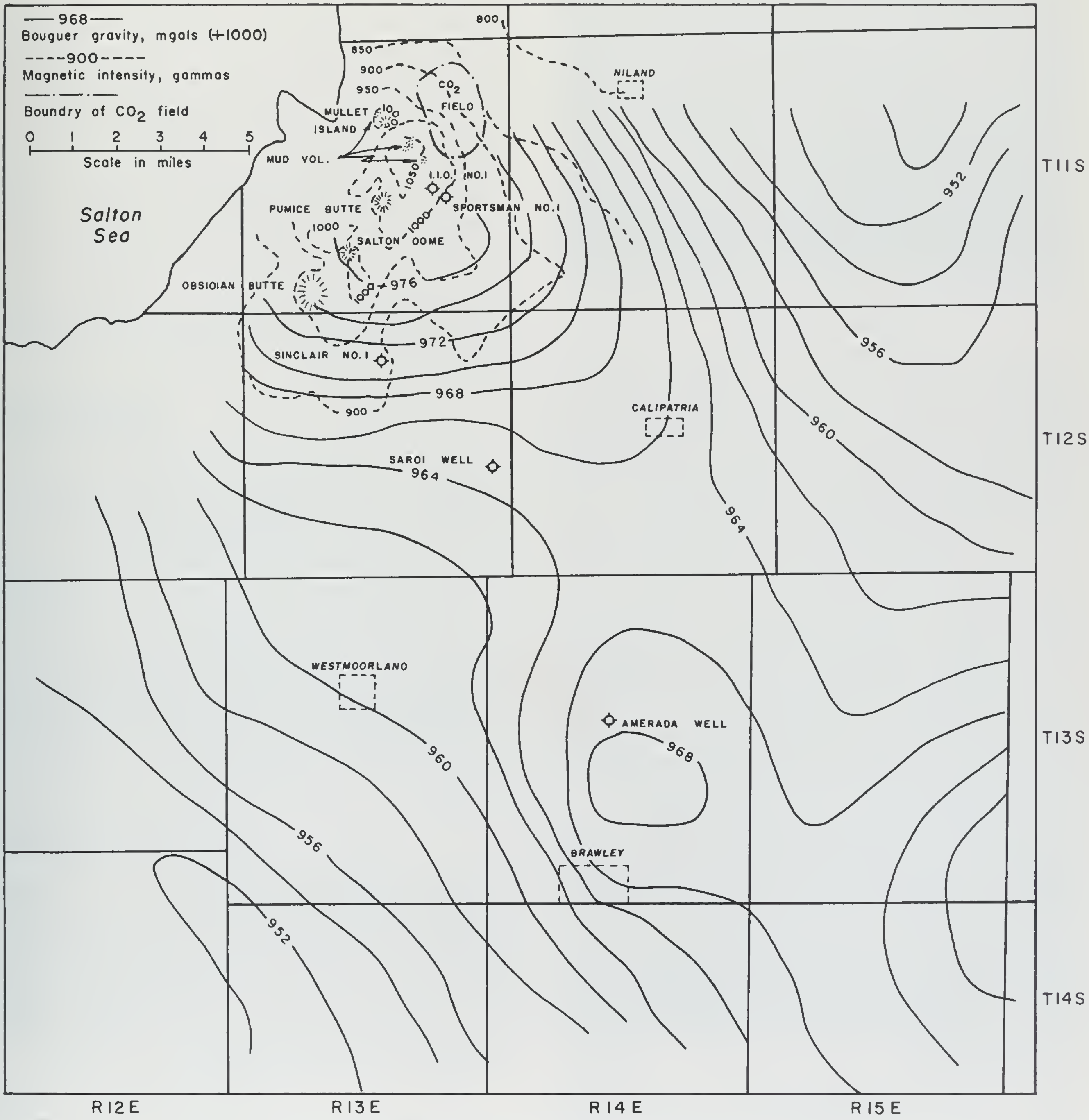


Figure 14. Saltan Sea thermal area. Magnetic data after Kelley and Saske, 1936; gravity data after Kovach, 1962.

Geology

The Salton Sea is approximately 30 miles long and 10 miles wide and stands at an elevation of 240 feet below sea level. The lake occupies the lowest part of a large topographic and structural depression which extends 175 miles from the head of the Gulf of California northwestward through the Colorado River delta, the Imperial Valley, and Salton Sea, to the Coachella Valley. The Colorado River delta protects the Salton basin from inundation by water from the Gulf of California.

In the vicinity of the Salton Sea this structural trough is about 75 miles wide. It is bordered on the west by the Peninsular Ranges, which are primarily granitic rocks of probable Cretaceous age (Dibblee, 1954, p. 21), and on the east by the Chocolate Mountains, a complex of Precambrian igneous and metamorphic rocks capped by Tertiary volcanic rocks.

The clastic sediments filling the Imperial depression represent essentially continuous deposition since Miocene time. The sediments attain a maximum exposed thickness of 16,500 feet in southwestern Imperial Valley, 18,700 feet in northwestern Imperial Valley and 8,600 feet in northeastern Coachella Valley (Dibblee, 1954, p. 21-22). Seismic data suggest that the fill is more than 20,000 feet thick in the central part of the depression. The sediments are primarily continental deposits consisting of fanglomerate, conglomerate and lacustrine sandstone and claystone. The Miocene Imperial Formation, however, is a shallow water marine claystone interbedded with oyster-shell reefs.

Three major right-lateral fault zones can be traced into Imperial Valley. The San Andreas zone can be followed along the northeast side of Coachella Valley and the San Jacinto and Elsinor fault zones have been mapped on the northwest side of Imperial Valley. There are only a few traces, however, which indicate the location of these faults on the flat, alluviated surface of the basin. Gravity surveys across the depression (Kovach, 1962, p. 2869-2870) have not been particularly successful in demonstrating the continuity of major fault zones within the depression, although gravity and seismic data confirm the presence of large vertical displacements beneath the valley alluvium.

The most striking surface feature of the Salton thermal area is the presence of five volcanic domes forming a five-mile-long north-northeast-trending arc which parallels the shore of the Salton Sea (figure 14). These domes, Mullet Island, Pumice Buttes (two coalesced domes), Salton Dome and Obsidian Buttes, are spaced at equal distances along the arc and rise about 100 feet above the surrounding alluviated surface. The domes are composed primarily of rhyolitic lavas, pumice, and obsidian.

Both a positive magnetic anomaly (Kelley and Soske, 1936) and a positive gravity anomaly (Kovach, 1962, figure 4, p. 2850) have been found distributed symmetrically about the southeast side of the volcanic arc (figure 14.) The fact that these geophysical anomalies coincide with a thermal anomaly, as well as with the position of the volcanic domes themselves, suggests that the dense magnetic mass underlying the area may be a cooling intrusive body from which the domes have been extruded.

There is also evidence suggesting that buried intrusive bodies may exist to the southeast of the Salton domes. A small positive gravity anomaly is located approximately 12 miles southeast of the volcanic domes in an area just north of Brawley (figure 14). In 1945, Amerada Petroleum Company drilled their Veysey No. 1 well in the SE¼, sec. 9, T.13S., R.14E., which is on the northwest flank of the gravity high. The well was drilled to 8,350 feet and abandoned because of the lack of oil indications. Although no steam was produced from this well, a temperature log indicated 138°C at 5,500 feet. The coexistence of a thermal and gravity anomaly in this area may indicate a cooling magma body. It is unlikely that the steam field extends between the volcanic domes and this small anomaly, because the Sardi Oil Co. well, drilled in sec. 24, T.12S., R.13E., (figure 14), did not encounter particularly high temperatures, although the thermal gradient here is also above normal.

Thermal activity

Surface thermal activity is confined to several groups of mud volcanoes extending southeast from Mullet Island on a line approximately 1 mile long, and to a group of mud pots just northwest of Mullet Island on an extension of the same line. Some of these vents emit only steam, water and carbon dioxide, while others erupt a viscous mud which forms a small cone around the orifice. Water temperatures around some of the vents have been measured as high as 79°C (Rook and Williams, 1942, p. 26), but generally the temperatures are considerably lower. Most of these mud volcanoes have been covered by a recent rise in the water level of the Salton Sea.

History of development

The first attempt to find natural steam in this area was in 1927 when three wells were drilled about one-half mile east of Mullet Island. The deepest of these wells was 1,473 feet and, although the circulating drilling mud was heated to a temperature of 118°C, the pressure and volume of steam obtained were insufficient for commercial purposes, and the project was abandoned (Rook and Williams, 1942, p. 19).

Although this first attempt to develop natural steam was unsuccessful, it demonstrated the probable existence of commercial accumulations of carbon dioxide gas. In 1932, a well was drilled on the southeast side of Salton Dome for the purpose of exploring for carbon dioxide. At a depth of 1,054 feet drilling was discontinued because the high temperature in the well made it impossible to handle the drill pipes when "coming out of the hole"; however, carbon dioxide was found at 310 feet. A second well was drilled about 2 miles east of Mullet Island to a depth of 750 feet where 99.1 percent carbon dioxide gas was found in considerable quantity (Rook and Williams, 1942). This was the discovery well of a field which was developed continuously from 1932 to 1954 and which produced over 2½ billion cubic feet of carbon dioxide gas.

Gas was obtained from wells drilled over an area approximately 3 miles long and 2 miles wide (figure 14), and principally from depths ranging between 200 and 700 feet. Addition of irrigation water to the Salton Sea in the early 1950s resulted in a rise of the lake level and was an important factor in forcing the abandonment of the field in 1954.

In late 1957 and early 1958, Kent Imperial Oil Co. drilled a wildcat well, the Sinclair No. 1, to a depth of 4,720 feet in NE ¼ sec. 10, T. 12 S., R. 13 E. (figure 14). Production casing of 3½-inch tubing was set to a depth of 4,692 feet and perforated with 4 holes at 3,310 feet. Instead of oil, however, steam and hot water were produced. A temperature log, taken several months after the well has been shut-in, recorded a temperature of 294° C at 4,600 feet.

In 1960 the Imperial Irrigation District granted a long term lease to O'Neill Geothermal, Inc. of Midland, Texas, for the purpose of developing natural steam resources in the Salton Sea thermal area.

Production

O'Neill's first well, Sportsman No. 1, was drilled in January and February 1961 near the center of sec. 23, T.11S., R.13E. (figure 14), to a depth of 4,729 feet. The formations encountered in the well are shown in the following table:

Depth (in feet)	*Formation*
0 to 1,685	Borrego-Brawley, Pleistocene to Pliocene, nonmarine
1,685 to 3,485	Imperial, upper Miocene, marine
3,485 to 3,805	Alverson Andesite, upper Miocene, volcanic
3,805 to 4,729	Split Mountain, middle Miocene, nonmarine

The 5½-inch OD production casing was perforated in the Split Mountain Formation with two shots per foot from 3,980′ to 4,100′; from 4,140′ to 4,250′; and from 4,560′ to 4,720′.

During a three day testing period 56,000 lb/hr steam and 258,000 lb/hr concentrated brine were produced from the well at 200 psig and 199° C. (tested by C. F. Braun & Co., Alhambra, Calif.).

Figure 15 shows the thermal gradient measured in Sportsman No. 1. Temperatures were recorded with a maximum-reading thermometer after the well had been static for approximately 30 days. Although the thermometer was graduated only up to 500° F, extrapolation of the smooth curve indicates a bottom hole temperature of 340° C (643° F), the highest temperature yet reported from a well drilled for natural steam.

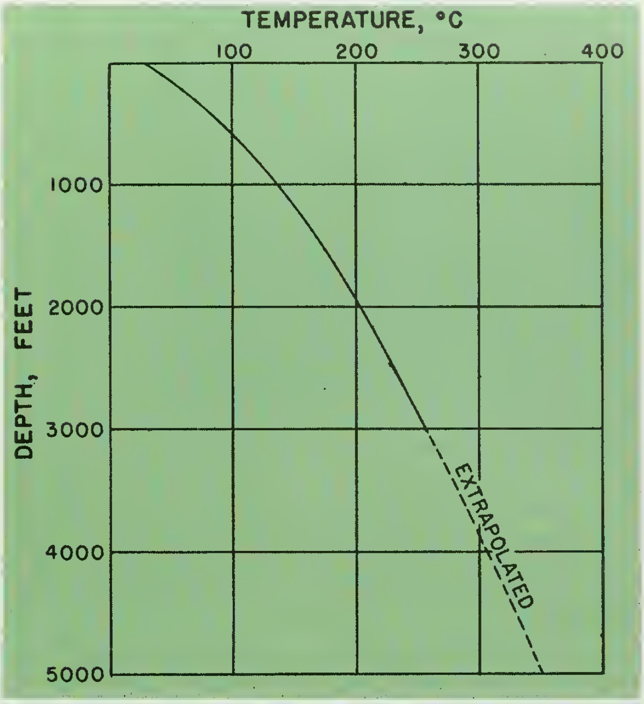


Figure 15. Thermal gradient of Sportsman No. 1 well, Salton Sea thermal area.

A representative analysis of the brine from Sportsman No. 1 is given in the following table.

Constituent	*ppm*
SiO_2	5.0
Fe	4200.0
Ca	34470.0
Mg	18.0
Na	70000.0
K	24000.0
Li	149.9
Cl	201756.7
B_4O_7	537.3
Total	334987.0

Analyst: Smith-Emery Co., Los Angeles

This sample, which had a specific gravity of 1.207, was taken on August 31, 1961. The pH of four brine samples taken from Sportsman No. 1 ranged from 4.82 to 6.1.

The unusually high brine content of this water may present a disposal problem, but on the other hand, the developers hope that it will be economically possible to recover potash and perhaps other chemicals from the brine.

O'Neill's second well, I.I.D. No. 1, was drilled in January 1962 at the center of NW¼ sec. 23, T.11S., R.13E. (figure 14), to a depth of 5,232 feet. The 7⅝-inch OD production casing was perforated with four shots per foot from 4,900 to 5,030 feet; from 5,040 to 5,140 feet; and from 5,168 to 5,212 feet. Tests made by the Rogers Engineering Co., San Francisco, Calif., in the summer of 1962, indicated a flow of 125,000 lb/hr steam and 500,500 lb/hr brine at wellhead conditions of 200 psig and 207° C. The deviation from saturation conditions is due to the high brine content of the effluent, which raises its boiling point by approximately 9.4° C.

The non-condensable gas content of the two O'Neill wells ranges between 0.2 percent and 0.3 percent by volume of the steam phase. On an average, the gas contains about 85 percent carbon dioxide, 2 percent oxygen and 0.5 percent methane, with the remainder principally composed of nitrogen. On several tests, however, small amounts of hydrogen sulfide and carbon monoxide were detected.

In November 1962, Western Geothermal, Inc. completed a steam well, the Sinclair No. 3, in the NW¼ sec. 10, T. 12 S., R. 13 E. at a depth of 5,326 feet. The well plan included 13⅜-inch surface casing set to 1,365 feet, and 8⅝-inch production casing set to the bottom and perforated at intervals from approximately 4,000 to 5,200 feet. Testing was begun during December 1962.

Exploratory drilling in this area is still insufficient to test the production limits of the Salton Sea thermal field adequately. Results from scattered wells, plus surface indications and geophysical data, however, suggest that production may be obtained over at least a 15-square-mile area. Preliminary estimates indicate that the power capacity of steam from Sportsman No. 1 well is 5,000 kw, and steam from I.I.D. No. 1 well can generate 10,000 to 14,000 kw, depending on the type of generating system utilized. If similar results are obtained over the entire area mentioned above, power production from this field could be very significant.

After this paper had gone to press, Standard Oil Co. reported a maximum temperature of 243° C at 13,150 feet in their "Wilson (et al.)" well, which was spudded in March, 1963. This well is located in sec. 20, T. 14 S., R. 15 E., approximately 20 miles southeast of the O'Neill wells, and on the southwest flank of a northeast-trending gravity high.

LARDERELLO, ITALY, 1850.

PART II. PROBLEMS OF NATURAL STEAM EXPLORATION AND DEVELOPMENT

In any new field of exploration, it is inevitable that problems will arise that cannot be immediately resolved by appealing to past experience. Three such problems which are particularly acute in the exploration and development of geothermal power are: 1) Preliminary evaluation of a thermal area; 2) Determining location and depth of production wells; 3) Estimation of steam reserve.

Various aspects of these problems and how they have been approached, both in California and abroad, will be discussed in the remainder of this report. It would be helpful, however, first to summarize some of the general geologic characteristics of steam fields.

Photo 11. Early system of drilling wells in thermal areas at Larderella, Italy. *From an old print.*

WITCHES' CAULDRON, THE GEYSERS.

GEOLOGIC CHARACTERISTICS OF STEAM FIELDS

All the thermal areas being developed throughout the world are located in regions of Cenozoic volcanism. It appears, therefore, that the source of heat for the thermal areas is related in some manner to the processes of volcanism and magmatic intrusion. If this is true, then it is reasonable to assume that thermal areas derive their heat either from buried flows of volcanic rock, or from still cooling intrusive bodies, which may be wholly or partially crystallized. Although it is difficult to evaluate the relative importance of extrusive rock as compared to intrusive bodies as heat sources, the latter would seem to be the more significant. Certainly at Larderello and The Geysers, where late Cenozoic volcanic flows do not underlie the steam fields, heat must be derived from an intrusive source. Cenozoic lava flows found in the region of these steam fields testify to youthful volcanic activity, and therefore to the probable presence of magmatic activity at depth.

In the thermal areas now under investigation throughout the world, the fissures which conduct thermal fluid to the surface are steeply dipping normal faults. These faults, however, have originated in two distinctly different structural environments. The Geysers and the Italian steam fields are in highland regions which have undergone recent orogenic uplift. These regions are characterized by complex horst and graben structures (Vecchia, 1960), which control the location of the thermal areas. Although located in volcanic belts, the thermal fluids do not rise in volcanic rock, but rather in the older, pre-volcanic rocks, which are brought to the surface on structural highs. On the other hand, geophysical evidence in New Zealand (Modriniak and Studt, 1959; Grindley, 1961), Casa Diablo, and the Salton Sea, indicate that these thermal areas are located within large structural depressions, rather than in areas of recent uplift. Even in this environment, however, there is evidence that some of the thermal areas are located near local, structural highs within the depression. These depressions are all closely associated with late Tertiary or Quaternary volcanism and may have a common origin as volcano-tectonic depressions. The geologic processes which relate magma movements to uplift and subsidence structures, volcanism, and thermal activity are not known.

In considering problems of exploration and development, it is important to distinguish between two types of steam fields: (a) the thermal area which yields dry or slightly superheated steam, and (b) the thermal area which produces saturated steam and hot water. The Geysers steam field and the two Italian fields of Larderello and Bagnore are of the dry steam type, while all the other thermal areas drilled thus far yield saturated steam and hot water. The principal factors which give rise to these two types of steam fields are: (a) the initial enthalpy or heat content of the thermal fluid, which is determined by the temperature of the heat source as well as by the thermodynamic and mechanical equilibrium conditions existing between the heat source and the thermal fluid in an open system, and (b) the amount by which the thermal fluid is diluted by cold, near-surface ground water.

This second factor is controlled principally by the structure and permeability of the rocks underlying the thermal area. If the conducting fissures are located in a structural depression filled with porous sediments and volcanic debris, the ascending thermal fluid will mix with the cold ground water which saturates the porous surface rocks. These conditions result in a thermal area which yields only saturated steam and hot water. If the conducting fissures intersect only impermeable rocks, as at The Geysers, or if they are covered by an impermeable layer which protects them from the downward percolation of near-surface ground water, as in Italy, the thermal fluid will be only slightly diluted by surface water, and the field may yield dry or perhaps superheated steam, depending on its initial enthalpy.

By the above remarks it is not meant to imply that the thermal fluid is entirely of magmatic origin. Whether the fluid is primarily meteoric or magmatic water is a separate problem which will be mentioned in the last section of this report. When considering the problems of evaluating and developing a steam field, it is more important to distinguish between thermal fluid and cold, locally derived ground water. This is because the problems encountered in producing natural steam are more closely related to the thermal and dynamic equilibriums existing between the thermal fluid and the local, near surface ground water, than to the equilibrium conditions existing between the thermal fluid and the heat source.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PRELIMINARY EVALUATION OF A THERMAL AREA

Prospecting for natural steam is not so much a problem of finding previously undiscovered thermal areas, but rather of deciding which of the known thermal areas have the most promising economic potential. In California alone there are 38 known thermal springs which have temperatures and flow rates comparable to the natural temperature and flow rate of The Geysers (Stearns, Stearns, and Waring, 1935). But how reliably can natural surface heat flow measurements be related to the ultimate recoverable heat energy from a given area?

Theoretically, mass flow and heat flow measurements may be taken on the surface, and an average enthalpy calculated for the thermal fluid. Assuming that the temperature curve of the fluid follows the boiling point curve of water, the maximum temperature which the fluid would reach on this curve, the depth to the maximum temperature region, and the potential power output from the area can all be calculated from the enthalpy of the fluid (Banwell, 1961, p. 3-8). This method of evaluation, however, can give only an approximation of the possible power potential because it is based on the assumption that: a) boreholes will not increase the mass flow of thermal fluid from the area, which they invariably do; and b) the enthalpy of the fluid emerging at the surface is the same as the enthalpy of the fluid throughout the thermal field, which it usually is not. The approximate degree of variation of the estimated natural heat flow from the actual heat flow attained by drilling can now be evaluated by using data from developed geothermal areas.

At Wairakei, which is a field producing saturated steam and water, preliminary surface measurements indicated a natural mass flow of 429 kg/sec of a fluid having a mean enthalpy of 394 cal/gm (Thompson, Banwell, Dawson, & Dickinson, 1961, p. 10). Although boreholes have increased the mass flow from the field by 3 to 5 times (Banwell, 1961, p. 14), the enthalpy of the borehole fluid was found to average only 270 cal/gm (Hunt, 1961, p. 22-23). The boreholes, therefore, have increased the heat flow by a factor of about 2 to 3.5 times.

At The Geysers, a dry steam field, production bores increased the mass flow about 20 fold, i.e., from approximately 40,000 lb/hr under natural conditions, to 800,000 lb/hr from the wells and the blowout. Because production is from below the zone where dry steam is mixed and condensed in the ground water blanket, the enthalpy of the borehole fluid, 667 cal/gm, is considerably higher than the enthalpy of the hot water flowing from thermal springs in Geyser Canyon. The high heat content of the dry steam as compared with the hot spring water, plus the high mass flow from the wells as compared with the natural spring flow, resulted in an induced heat flow approximately 170 times the natural heat flow.

Because of the great discrepancy between the maximum power potential implied by surface measurements and the actual power that is eventually produced from dry steam areas, as compared with an area producing saturated steam and water, it would be advantageous to determine from surface measurements if a particular area is of the dry or wet steam type. A method has been proposed for distinguishing these two types of thermal areas on the basis of the chemical composition of the thermal water (White, 1961, p. 3). Dry steam areas are characterized by acid-sulfate springs, with insignificant chloride content, while springs flowing from "wet" steam fields have a high chloride content. White believes that chloride is transported from the heat source in an alkali chloride solution. If a steam phase forms in the thermal system, chloride is left behind in the liquid phase rather than being transported through to the surface with the steam. This mechanism may provide a convenient method for predicting whether a thermal area will produce dry steam or saturated steam and water.

An impermeable cap over the thermal fluid reservoir can greatly reduce the natural surface heat flow from a thermal area, making preliminary evaluation of the area extremely difficult. Access of the thermal fluid to the surface may be blocked by deposition of calcite and silica in the fracture system through which the fluid is circulating. Deposition should be particularly rapid in the upper end of the fracture system, because it is in this near-surface region that the temperature and pressure of the fluid are most rapidly decreasing. Although there are no examples cited in the literature where the flow of thermal fluid to the surface has been blocked by mineral deposition under natural conditions, many wells drilled in thermal fields have eventually become blocked in this manner. It is reasonable to assume, therefore, that this same mechanism will operate under natural conditions.

Another type of reservoir capping is exemplified by the Italian steam fields where steam is produced from highly porous limestone and anhydrite beds which are overlain by impermeable shales. Although the surface manifestations of steam in the Bagnore area were very meager, i.e., a few warm springs ranging from 20° C to 50° C (plus some cold H_2S and CO_2 gas vents), 200,000 kg/hr of thermal fluid are now produced from 5 bores (Burgassi, 1961, p. 9-11). Preliminary evaluation of this type of field must be based on considerable structural information and experience with similar steam-bearing zones in the region.

It can be concluded from the above discussion that the absence of intense natural thermal activity is not necessarily a negative factor in the preliminary evaluation of a thermal area. Furthermore, natural heat flow measurements usually give only a minimum estimate of the ultimate heat flow which might be induced by drilling wells.

It should also be noted that the presence or absence of young volcanic rocks in the immediate vicinity of the prospect is not a significant factor for preliminary evaluation. For example, the closest outcrop of volcanic rocks is 8 miles from the Larderello steam field. Structural depressions related to Cenozoic volcanism are probably more significant surface indications of magmatic activity at depth than the actual presence of volcanic rock in the immediate vicinity of the prospect area.

DETERMINING LOCATION AND DEPTH OF PRODUCTION WELLS

In locating production wells, the objective should be to intersect the conducting fissures at an optimum depth considering both economic and geologic factors.

In dry steam fields, it would not be practical to intersect the fissures much below the impermeable capping formation or the ground water blanket overlying the steam, because rapid increases of temperature and pressure with depth would not be expected within the steam zone. On the other hand, in saturated steam-water fields, temperature and pressure can be expected to increase with depth on a gradient defined by the boiling point–pressure curve of water. The maximum temperature which can be reached by drilling will depend on the initial enthalpy of the thermal fluid, i.e., the enthalpy of the fluid before it is diluted by cold, near-surface ground water. In such cases, the optimum well depth should be determined by the practical economic depth of drilling. At Wairakei, for example, holes are located about 200 feet from the traces of the major faults and on the downdropped side so that the fissure is intersected between depths of 1000 and 2000 feet where temperatures are reasonably high (Grindley, 1961, p. 5). Deeper holes are generally avoided because they would necessitate drilling into hard ignimbrite, which would be time consuming and expensive.

In areas where the conducting fissures intersect permeable strata near the surface, the thermal fluid spreads laterally into the permeable rocks. Because the area over which the fluid migrates is so much larger than the cross-sectional area of the narrow fissures from which it flows, the fluid in the permeable beds is easier to locate and consequently cheaper to produce. On the other hand, the migrating fluid exists under considerably lower temperature and pressure conditions than the fluid in the conducting fissures. At Wairakei approximately 40 percent of the steam utilized in the turbines is taken directly from the fissures at pressures ranging from 180 to 220 psig, the remaining 60 percent is produced from the surrounding permeable formations at pressures ranging from 50 to 85 psig (Armstead, 1961, p. 14). The expense and effort which should be put into finding high pressure steam in a field of this nature is ultimately determined by the design and steam requirements of the turbine. Obviously, if there is a choice as to the type of steam that can be produced, an intensive study should be made of the field characteristics, and the choice of turbine design based on the resulting data.

Well location becomes extremely difficult in those areas where the fault trace and dip cannot be accurately determined from surface observation. This is a problem common to the Wairakei, Casa Diablo, and Salton Sea areas where the collapse structure is filled with volcanic flows and tuffs, lake beds, and recent alluvium. In such cases, the faults are either covered by young material deposited in the rapidly sinking basin, or the surface formation is too soft and homogeneous to produce recognizable fault scarps. The alignment of hot springs is not always the best guide for locating the fault trace, because the location of springs is controlled by ground water migration and the surface drainage pattern, as well as by the fault trace itself.

The problem of well location in areas of this nature has been met with some success in New Zealand and Italy by the application of various geophysical techniques which include gravity, magnetic, temperature, and resistivity surveys. The applicability of any specific geophysical method, as will be demonstrated by the following examples, is principally determined by subsurface geologic conditions.

In general, gravity surveys have been helpful in delineating the major depressions in which the thermal areas occur, as well as structures in the basement underlying the volcanic and sedimentary rocks filling the depression. These structural depressions are marked by negative gravity anomalies with a gravity relief in the range of 20 to 40 milligals.

Positive gravity anomalies, small in area compared to the large structural depression in which they occur, have been observed at Casa Diablo and the Salton Sea. These gravity anomalies correspond to positive aeromagnetic anomalies and are interpreted as being due to buried volcanic or intrusive rock. If such is the case, then these gravity and magnetic anomalies may be useful for locating local heat sources buried within the depression. On the other hand, it is possible that these gravity and magnetic anomalies are caused by some feature in the basement rock unrelated to magmatic processes and, therefore, they must be interpreted with caution.

Gravity and magnetic surveys have not been particularly helpful in distinguishing production fissures within the structural depressions because of the uniform density and magnetic characteristics of the near surface material filling the depression. It has been noted, however, that detailed land magnetic surveys reveal magnetic lows over thermal areas due to hydrothermal alteration of magnetite to pyrite (Studt, 1961, p. 4). If the land magnetic survey can be interpreted in the light of subsurface information, including lithology, alteration, and fluid movement, it may be possible to locate areas in which the thermal fluid is being fed into a reservoir (Studt, 1959). These areas seem to be characterized by more intense alteration of magnetite to pyrite than other parts of the reservoir, and consequently, produce near-surface negative gravity anomalies.

Temperature surveys are probably the most satisfactory geophysical method used to locate drill holes in thermal areas when the conducting fissures themselves are not directly observable. In New Zealand, temperatures are taken with a thermocouple at 60 meter intervals and one meter depth (Thompson, Banwell, Dawson, and Dickinson, 1961, p. 1-3). The size of the area surveyed is determined by the temperature limits of 1° C to 50° C above ambient at 1 meter depth. The potentiometer readings for each station are computed to degrees Centigrade, corrected for seasonal change, and contours are drawn at the outer boundary (1° C above local ambient), and on the 20° C and 50° C isotherms. These surveys have shown that measurably hot areas extend well beyond the directly observable surface activity, and make it possible to locate prospect holes efficiently.

Regional thermal surveys have been undertaken in Italy in which the geothermal gradient was measured in 30-meter prospect holes (Burgassi, Battini and Mouton, 1961). The holes were drilled along lines perpendicular to structure, and at intervals ranging from 300 to 600 meters. Although a good correlation was found between high thermal gradients and the steam producing zones, this type of survey is considered to be of a more regional significance, and is comparable to gravity and aeromagnetic surveys, rather than being useful for locating specific production fissures.

Electric resistivity surveys, in conjunction with gravity surveys, have been very helpful in locating the major faults that bound the horst and graben structures characteristic of the Italian steam fields. The electrically resistant anhydrite and carbonate rocks, which contain the steam reservoirs, are overlain by an impermeable, conductive shale. The resistivity method is successful because the thickness of the shale cover is characteristic of each fault block so that the resistivity survey shows the position of the faults as well as the comparative thickness of the shale, and therefore, the depth to the reservoir rocks (Mazzoni, A. and Breusse, J. J., 1954; Alfano, 1960; Battini and Menut, 1961).

The electrical resistivity method is useful not only for determining geologic structure, but also can indicate the presence of a geothermally heated zone. It has been found in Italy that ground heated from 17° C to 150° C decreases in resistivity by a factor of 5 and if heated from 17° C to 280° C, its resistivity decreases by a factor of 9 (Breusse, 1961). The effect of temperature on resistivity has been successfully utilized for natural steam exporation at Kawerau, New Zealand (Studt, 1958a, p. 230-235). In that area, Studt found that, at the water table (10-20 feet deep), the resistivity drops abruptly to several hundred ohm-meters in cold country, and to several tens of ohm-meters in hot. Resistivity surveys utilizing this heat effect are best applied in areas having uniform surface geology and uniform depth to the water table.

Geochemical investigations have been emphasized at Wairakei since development first began in 1950. This work consists of detailed sampling and chemical analysis of natural hot spring and borehole discharges at regular time intervals. Interpretation of these data has been extremely difficult because of the complex chemical reactions occurring between the thermal fluid and the country rock, and the varying amounts of mixing and dilution of the thermal fluid with surface water. It was found that the sampling of springs and shallow prospect bores in the early stages of development gave a misleading idea of many of the chemical characteristics of the hydrothermal system and only by continuous observation and comparisons, over a period of 5 years, could an accurate picture be obtained.

Probably the most significant information obtained from the geochemical study was the correlation of the chemistry of the hot water with the formation of various hydrothermal minerals at different levels. Steiner (1953, 1955) has shown that the rising thermal water interacts with the country rock to form various zones of hydrothermal alteration. The essential changes in the thermal fluid resulting from its interaction with the country rock include loss of some potassium and rubidium, very slight loss of lithium, caesium and magnesium, and gain of calcium. As a result of these reactions, the drillholes which discharge water with the lowest Na/K and Na/Rb ratios, or highest Na/Ca and Li/Ca ratios are closest to a point where the waters enter the system from greater depths and have had the least contact with the country rock (Ellis and Wilson, 1960; Ellis, 1961).

ESTIMATION OF STEAM RESERVE

Early in the development of a new thermal area it would be highly desirable to estimate the total steam reserve of the field. This information is important both to encourage capital investment for financing further development and to determine the most efficient type and capacity of turbine-generator unit to be installed. Mainly due to the lack of knowledge concerning the mechanics of steam reservoirs, however, no satisfactory estimates of steam reserves have been made for any of the fields so far developed.

The customary method of calculating natural gas and petroleum reserves—that is, by plotting decrease of reservoir pressure against cumulative production—cannot be applied to steam reservoirs. This method can be applied to natural gas and oil fields because a specific volume of fluid exists in the reservoir at a specific initial pressure. Assuming a reservoir of constant volume, the fluid reserve at any stage of production will be related to the decrease in reservoir pressure caused by the withdrawal of fluid. It cannot be assumed, however, that a steam reservoir contains a fixed initial volume of fluid existing under static conditions.

It has been shown by a study of the variations in the deuterium and O^{18} concentrations in surface and hot spring waters (Craig, Boato and White, 1956) that the major amount of hot spring water is meteoric rather than magmatic in origin. It therefore must be assumed that the thermal fluid reservoir is not static, but consists of a large natural convective system. By study of the C^{12}, C^{13}, and C^{14} isotopes in the thermal system at Steamboat Springs, Nevada, it has been further shown that the descending meteoric water spends at least 30,000 to 300,000 years underground, depending on the type of circulation (Craig, 1962).

In view of the evidence that thermal fluid reservoirs are actually dynamic circulatory systems of considerable capacity, the estimation of absolute steam reserves no longer has meaning. Instead, the problem becomes one of estimating not only the amount of heat contained in the heat source but also the rate of heat flow from the source to the thermal fluid, and the rate of fluid flow through the circulatory system.

In order to estimate the total amount of heat available in the source, it would be necessary to know its size, internal temperature gradients, and degree of crystallization. The rate of heat withdrawal from the source depends on the shape, structure and fluid content of the heat source; structure, and permeability of the rock surrounding the source; and the thermal gradient within the circulating fluid and surrounding country rock. Because this type of information has not been obtained, a quantitative answer to the question of steam reserves cannot be given.

In a thermal system such as at Wairakei, where heat coming from a magmatic source accumulates in a large aquifer, it is possible to estimate the amount of heat stored in the secondary reservoir. Banwell (1955, p. 61) has calculated that the heat stored within 3,000 feet of surface at Wairakei is 3.4×10^6 cal/sq cm (referred to 100° C). Over 80 percent of this energy, which was contained in 1.68×10^8 metric tons of steam and hot water, has been withdrawn from the reservoir over a period of 8 years (Banwell, 1961, p. 14). During this period, the natural surface heat flow, as well as the temperature of the fluid in the producing wells, has remained nearly constant. In order to evaluate steam reserves in a thermal system of this type, it is necessary to know whether heat is being produced mainly from the heat stored in the secondary reservoir, or whether the wells have tapped the channels feeding thermal fluid into the reservoir. In light of the fact that reservoir pressures are generally decreasing, Studt (1958 b) has concluded that some of the heat produced at Wairakei is coming from storage in the reservoir with consequent inflow of cold water. In order to utilize all the available stored heat, as well as estimate the life expectancy of this type of steam field, it is important to locate these channels of thermal fluid and cold water ingress to the reservoir and also determine the extent to which the natural equilibrium conditions of heat flow have been upset by exploitation.

The geologic processes which control the life expectancy of a thermal field are extremely complex, and our understanding of them is as yet rudimentary. Nevertheless, it is necessary to investigate these processes not only in order to find the answers to the problems discussed in this report, but also to evaluate the relative importance of geothermal power as a future source of energy. These problems eventually will be solved as more thermal areas are explored by the drill and analyzed by geologic, geophysical, and geochemical methods. From a more immediate point of view, however, it should be remembered that a power installation is amortized over an average period of 20 years, which is an extremely short interval compared to the duration of the geologic processes related to natural thermal activity.

REFERENCES

Alfano, L., 1960, Geolectrical explorations for natural steam near "Monte Amiata": Quaderni di Geofisica Applicata, vol. 21, p. 3-17.

Allen, E. T., and Day, A. C., 1921, Steam wells and other thermal activity at "The Geysers", Calif.: Carnegie Inst. Washington, Pub. 378, 106 p.

Anderson, E. T., 1961, How world's hottest hole was drilled: Petroleum Engineer, vol. 33, no. 11, p. 47-51.

Armstead, H. C. H., 1961, Geothermal power development at Wairakei, New Zealand: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/4, 20 p.

Banwell, C. J., 1955, Physical investigations, in Grange, L. I., editor, Geothermal steam for power in New Zealand: New Zealand Department of Scientific and Industrial Research Bull. 117, Chap. 6, p. 45-74.

Banwell, C. J., 1961, Geothermal drillholes—physical investigations: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/53, 24 p.

Battini, Ferdinando, and Menut, P., 1961, Structural study of the Roccastrada zone in prospecting for steam by geophysical, gravimetric and electrical methods: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/26, 19 p.

Beck, A. C., and Robertson, E. I., 1955, Geology and geophysics, in Grange, L.I., editor, Geothermal steam for power in New Zealand: New Zealand Department of Scientific and Industrial Research Bull. 117, Chap. 2, p. 15-19.

Breusse, J. J., 1961, Contributions des methodes geophysiques a la prospection des champs geothermiques: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/25, 6 p.

Brice, James C., 1953, Geology of Lower Lake quadrangle, California: California Div. Mines Bull. 166, 72 p.

Bruce, A. W., and Albritton, B. C., 1959, Generation of power from geothermal steam at The Geysers power plant: presented at spring convention of Am. Soc. Civil Engineers, Los Angeles, Calif. (mimeo), 17 p.

Bruce, Albert W., 1961, Experience in generating geothermal power at The Geysers Power Plant, Sonoma County, California; U.S.A.: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/8, 20 p.

Burgassi, Renato, 1961, Prospecting of geothermal fields and exploration necessary for their adequate exploitation, performed in various regions of Italy: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/65, 30 p.

Burgassi, R., Battini, F., and Mouton, J., 1961, Geothermal prospecting for telluric energy, United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/61, 8 p.

Cleveland, George B., 1961, Economic geology of the Long Valley diatomaceous earth deposit, Mono County, California: California Div. Mines Map Sheet 1.

Cleveland, in press, Geology of the Little Antelope Valley clay deposits, Mono County, California: California Div. Mines and Geology Special Rept. 72.

Craig, H., Boato, G., and White, D., 1956, Isotopic geochemistry of thermal waters: Natl. Research Council Nuclear Sciences Series, Rept. No. 19, Nuclear Processes in Geologic Settings, p. 29-44.

Craig, H., 1962, C^{12}, C^{13} and C^{14} concentrations in volcanic gases (abstract): Jour. of Geophys. Research, vol. 67, no. 4, p. 1633.

Dibblee, T. W., 1954, Geology of the Imperial Valley region, California: California Div. Mines Bull. 170, Chap. 2, p. 21-28.

Ellis, A. J. and Wilson, S. H., 1960, The geochemistry of alkali metal ions in the Wairakei hydrothermal system: New Zealand Jour. Geology Geophysics, vol. 3, p. 593-617.

Ellis, A. J., 1961, Geothermal drillholes—chemical investigations: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/42, 26 p.

English, Earl F., 1961, Methods and equipment for harnessing geothermal energy at The Geysers, California, U.S.A.: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/51, 21 p.

Gilbert, Charles M., 1938, Welded tuff in eastern California: Geol. Soc. America Bull., vol. 49, p. 1829-1862.

Grindley, G. W., 1961, Geology of New Zealand geothermal steam fields: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/34, 17 p.

Henderson, John R., White, Bernard L., and others, 1963, Aeromagnetic map of Long Valley and northern Owens Valley, California: U.S. Geological Survey Geophysical Investigation Map GP-329.

Hunt, A. M., 1961, The measurement of borehole discharges, downhole temperatures and pressures, and surface heat flows at Wairakei: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/19, 23 p.

Kelley, U. C., and Soske, J. L., 1936, Origin of the Salton volcanic domes, Salton Sea, California: Jour. Geology, vol. 44, p. 496-509.

Kovach, Robert L., Allen, C. R., and Press, F., 1962, Geophysical investigations in the Colorado Delta region. Jour. Geophys. Research, vol. 67, no. 7, p. 2845-2871.

Mazzoni, A., and Breusse, J. J., 1954, Application de la prospection electrique a la tectonique pour la recherche de vapeur naturelle a Larderello (Italie): Internat. Geol. Cong., 19th, Algers 1952, Section 15, Fascicule 17, p. 161-168.

Modriniak, N. and Studt, F. E., 1959, Geological structure and volcanism of the Taupo-Tarawera District: New Zealand Jour. Geology Geophysics, vol. 2, p. 654-684.

Pakiser, L. C., 1961, Gravity, volcanism, and crustal deformation in Long Valley, California: U.S. Geol. Survey Prof. Paper 424-B, p. 250-253.

Rinehart, C. Dean, and Ross, D. C., 1956, Economic geology of the Casa Diablo quadrangle, California: California Div. Mines Special Rept. 48, 17 p.

Rinehart, C. Dean, and Ross, D. C., in press, Geology of the Mt. Morrison quadrangle, California, U.S. Geol. Survey.

Rook, Stephen H., and Williams, G. C., 1942, Imperial carbon dioxide gas field: Summary of operations—California Oil Fields, California Div. Oil and Gas, July-December, vol. 28, no. 2, p. 12-33.

Stearns, N. D., Stearns, H. T., and Waring, G. A., 1935, Thermal springs in the U.S.: U.S. Geol. Survey Water-Supply Paper 679-B, p. 59-191.

Steiner, A., 1953, Hydrothermal rock alteration at Wairakei, New Zealand: Econ. Geology, vol. 48, p. 1-13.

Steiner, A., 1955, Hydrothermal rock alternation, *in* Grange, L.I., editor, Geothermal steam for power in New Zealand: New Zealand Department of Scientific and Industrial Research Bull. 117, Chap. 3, p. 21-26.

Studt, F. E., 1958 a, Geophysical reconnaissance at Kawerau, New Zealand: New Zealand Jour. Geology Geophysics, vol. 1, p. 219-246.

Studt, F. E., 1958 b, The Wairakei hydrothermal field under exploitation: New Zealand Jour. Geology Geophysics, vol. 1, p. 703-723.

Studt, F. E., 1959, Magnetic survey of the Wairakei hydrothermal field: New Zealand Jour. Geology Geophysics, vol. 2, p. 746-754.

Studt, F. D., 1961, Geophysical prospecting in New Zealand's hydrothermal fields: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/33, 11 p.

Thompson, G. E. K., Banwell, C. J., Dawson, G. B., and Dickinson, D. J., 1961, Prospecting of hydrothermal areas by surface thermal surveys: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/54, 25 p.

Vecchia, Orlando, 1960, Gravimetric exploration for natural steam in Tuscany: Quaderni di Geofisica Applicata, vol. 21, p. 18-27.

White, D. E., 1957, Thermal waters of volcanic origin: Geol. Soc. America Bull., vol. 68, p. 1637-1658.

White, D. E., 1961, Preliminary evaluation of geothermal areas by geochemistry, geology, and shallow drilling: United Nations Conference on New Sources of Energy, Paper E/Conf. 35/G/2, 12 p.

White, D. E., 1963, Geothermal brine well: mile-deep hole may tap ore-bearing magmatic water and rocks undergoing metamorphism: Science, vol. 139, no. 3558, p. 919-922.

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