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A VAPOR-DOMINATED RESERVOIR EXCEEDING 600°F AT THE GEYSERS SONOMA COUNTY, CALIFORNIA

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ABSTRACT

A high-temperature vapor-dominated reservoir underlies a portion of the Northwest Geysers area, Sonoma County, California. The high-temperature reservoir (HTR) is defined by flowing fluid temperatures exceeding 500°F, rock temperatures apparently exceeding 600°F and steam enthalpies of about 1320 BTU/lb. Steam from existing wells drilled in the Northwest Geysers is produced from both a "typical" Geysers reservoir and the HTR. In all cases, the HTR is in the lower portion of the wells and is overlain by a "typical" Geysers reservoir. Depth to the high-temperature reservoir is relatively uniform at about -5900 ft subsea. There are no identified lithologic or mineralogic conditions that separate the HTR from the "typical" reservoir, although the two reservoirs are vertically distinct and can be located in most wells to within about 200 ft by the use of downhole temperature-depth measurements. Gas concentrations in steam from the HTR are higher (6 to 9 wt %) than from the "typical" Geysers reservoir (0.85 to 2.6 wt %). Steam from the HTR is enriched in chloride and the heavy isotopes of water relative to the "typical" reservoir. Available static and dynamic measurements show pressures are subhydrostatic in both reservoirs with no anomalous differences between the two; the HTR pressure being near 520 psia at sea level datum. The small observed differences in pressure between the reservoirs appear to vary along a steam density gradient. It is postulated that the Northwest Geysers area evolved more slowly toward vapor-dominated conditions than other parts of The Geysers field because of its poor connection with the surface. In this paper, a model is presented in which the boundary between the HTR and "typical" reservoir is a thermodynamic feature only, resulting from recent deep venting of a liquid-dominated system in which conduction is still an important component of heat transfer.

INTRODUCTION

The presence of high temperatures (>600°F) in wells drilled by GEO Operator Corporation (GEOOC), a wholly owned subsidiary of Geothermal Resources International, Inc. (GEO), in the Northwest Geysers (Figure 1) was first recognized in 1982 from temperatures measured during downhole directional well surveys. With the availability of high-temperature logging tools, the presence of flowing high-temperature (>656°F) steam was recorded in January 1984.

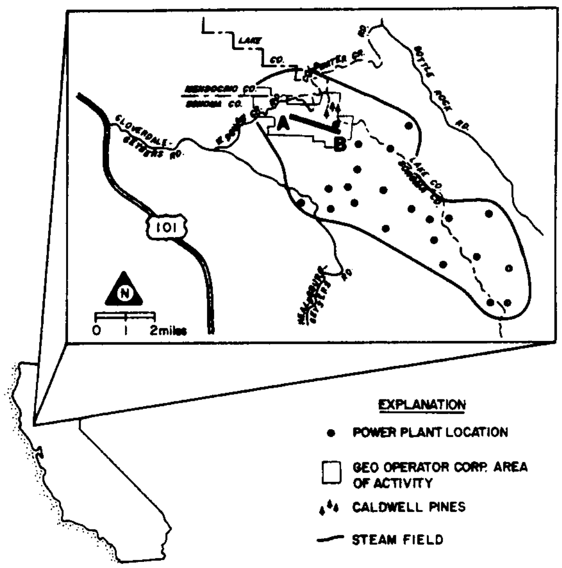


Figure 1: Map of The Geysers with location of geologic cross section (A-B) of Figure 2.

Wells in leases offsetting the Northwest Geysers area of GEOOC also penetrate (a) high-temperature reservoir(s) (Sternfeld and others, 1983 and Beall, 1985). Because there are at least two deep (±10,000 ft) wells that do not encounter high temperatures between the GEOOC and high-temperature wells on other leases, the HTR in the GEOOC area is treated in this paper as if it were a separate reservoir not related to others.

Wells penetrating the Northwest Geysers HTR, referred to as high-temperature wells later in this paper, are the subject of previous papers. Drenick (1986) discussed the logging and interpretation of a single high-temperature well and Haizlip (1985) described enriched isotope composition in steam from Northwest Geysers wells.

The primary purpose of this paper is to document the existence of a HTR by describing the areal extent and characteristics of the HTR penetrated by GEOOC wells. In this paper, it will be shown that the temperature and enthalpy of steam in the HTR are significantly different from the "typical" Geysers reservoir steam. It will also be shown that rock type, secondary mineralogy and pressure do not appear to be diagnostic of the HTR. Finally, a conceptual model is presented to explain the presence of the HTR in the Northwest Geysers.

GEOLOGIC SETTING

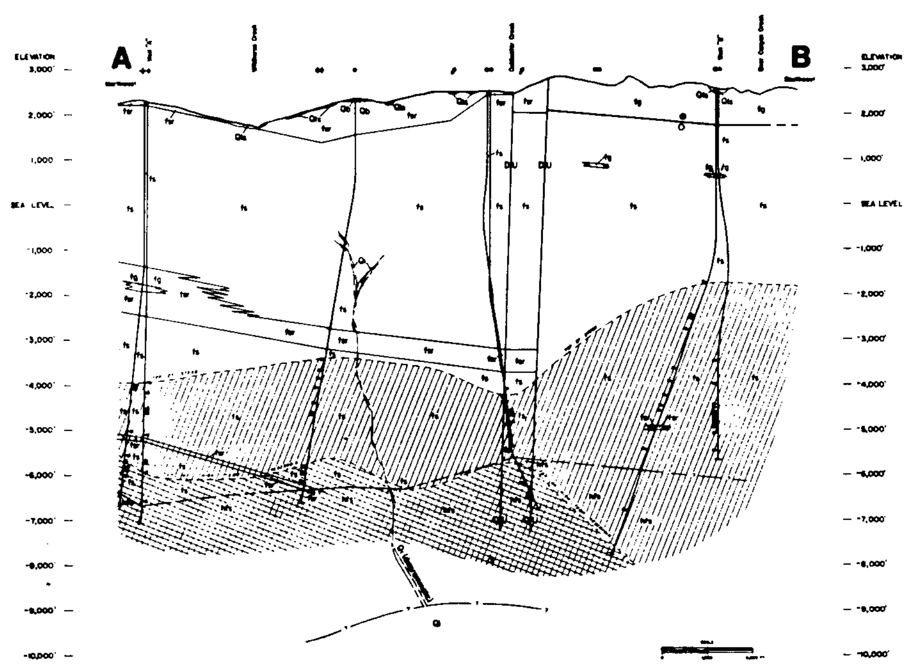
Lithology and Secondary Mineralogy

Most wells drilled by GEOOC in the Northwest Geysers are drilled from the surface to total depth in Franciscan graywacke (Figure 2). The only interruptions of the graywacke are occasional, thin (usually less than 100 ft) units of greenstone and chert, and tectonic-related melanges which include serpentinite, blueschist and clay. No significant changes in primary Franciscan formation metamorphic grade or detrital composition are observable between the graywackes of the unfractured rock overlying the top of steam, the "typical" reservoir and the HTR. These weakly metamorphosed metasedimentary rocks are reconstituted to textural grade 1 described by Blake and others (1967).

There is a gradational alteration of the graywacke with depth due to hydrothermal as well as thermal metamorphism. With increasing depth, the graywacke becomes hornfelsic as matrix materials and then framework grains become increasingly recrystallized. Tourmalinized reservoir rock (single hatching on the lithology column of Figure 3) displays weak to moderately developed schistose textures. At greater depths, the reservoir is noticeably hornfelsic (double hatching on the lithology column of Figure 3).

The HTR is most often encountered within hornfelsic graywacke and sometimes within the tourmalinized zone inferring a causal relationship. However, the correlation is fortuitous as "typical" steam reservoir conditions are also found in tourmaline-bearing and hornfelsic altered rocks in other Northwest Geysers wells. The apparent correlation between the hornfels and the HTR is simply a depth relationship.

The hornfels indicates intrusive rocks are relatively near. Publicly available, open-file well records from the California Division of Oil and Gas indicate that hornfels aureoles occur within 1500 ft or more above felsite bodies in the Southeast and Central Geysers areas. The nearly planar distribution of hornfelsic graywacke (Figure 2) indicates that felsite intrusives probably underlie a large extent of the GEOOC portion of the field although only two subsurface occurrences of intrusives are as yet drilled in the Northwest Geysers. Additional indirect evidence for Quaternary intrusion comes from geomorphological studies of the area. Circular anomalies, barbed tributaries and arcuate stream segments are evidence for



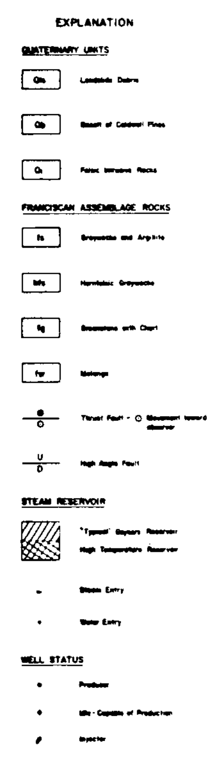


Figure 2: Geologic cross section through Northwest Geysers area (A-B) of Figure 1.

recent uplift and associated tensional faulting related to intrusive activity (Bebber, 1986).

There is no evidence to suggest that secondary minerals form a seal between the HTR and "typical" reservoir. The percentage of vein-filling minerals to total rock in both reservoirs is typically 1 to 3% and there is not a unique assemblage of minerals restricted to either reservoir. At least three generations of secondary minerals are recognized in The Geysers (Figure 3) as determined from petrologic and isotopic studies (Lambert, 1976; Sternfeld, 1981). The dominant secondary mineralization is a strongly zoned succession of Quaternary mineral assemblages deposited by a liquid-dominated hydrothermal system induced by felsite intrusion. A later Quaternary set of retrograde minerals superimposed over the first, occurs sporadically throughout the steam reservoir and tends to correlate with steam entries in well bores. This later Quaternary mineral assemblage, characterized by prehnite and axinite, probably represents the last forming minerals precipitated from liquid during the vaporization process that transformed The Geysers from a liquid-dominated to a vapor-dominated system. The temperature of formation for prehnite in active geothermal systems, 460 to 680°F (Bird and others, 1984), corresponds with the range of observed temperatures in both reservoirs.

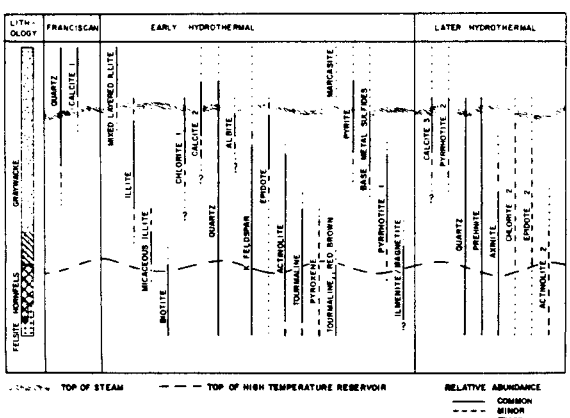


Figure 3: Generalized secondary mineralogy at The Geysers.

Surface Geothermal Manifestations

Unlike the Central and Southeast Geysers, relatively few surficial hydrothermal manifestations, i.e., vent areas, occur in the Northwest Geysers as shown in Figure 4. Presently, the only known venting of noncondensible gases in the portion of the Northwest Geysers developed by GEOOC are confined along the traces of two faults. These gases are from dry gas vents and cold springs which have anomalous concentrations of sulfate, carbon dioxide, boron and carbonate. Because hydrothermal alteration is often evidence for past geothermal activity, it is concluded that the surficial geothermal manifestations in the Northwest Geysers were also of limited extent in the past as in the present.
The spatial relationship of noncondensible gas in steam from geothermal wells to surficial geothermal manifestations is also shown in Figure 4. As discussed later in this paper, the high gas content in the steam from wells of the Northwest Geysers and the relatively few surface manifestations are believed to be directly related.

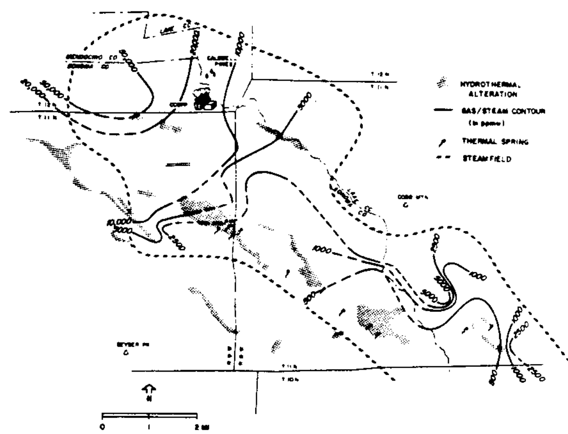


Figure 4: Relationship of gas/steam ratios from wells to vent areas in The Geysers.

RESERVOIR DATA

Temperature Measurements

The HTR is recognized primarily by downhole temperature measurements. Wellhead data are also useful in the recognition of wells penetrating the HTR but are not diagnostic in some cases where the relative steam contribution from the HTR to the total flow rate of the well is low (Table 1).

TABLE 1
Northwest Geysers
Sonoma County, California

WELLHEAD DATA

WELLS PENETRATING "TYPICAL" GEYSERS RESERVOIR (≤480°F)

Enthalpy (BTU/lb)	Total N/C Gas (ppmw)	H_2S (ppmw)	Isotopes vs. SMOW** $\delta^{18}O$ (°/oo)	δD (°/oo)	Chloride (ppmw)
1195-1211	8500-25700	250-870	-0.2	-50	<1

WELLS PENETRATING HIGH TEMPERATURE RESERVOIR (≥500°F)

Enthalpy* (BTU/lb.)	Total N/C* Gas (ppmw)	H_2S* (ppmw)	Isotopes vs. SMOW** $\delta^{18}O$ (°/oo)*	δD (°/oo)*	Chloride (ppmw)
1200-1242	26,000 - 76,700	750-1660	+1.4	-44	15-150

* Note: Values represent combined steam flow from both the HTR and "typical" Geysers reservoir. The relative contribution from the HTR at the wellhead ranges from >5 to 69% of the total flow. The highest values are from wells with the greatest steam contribution from the HTR.

** Isotope values are weighted averages.

Publicly available temperature-depth data for wells in the Central Geysers (Lipman and others, 1978 and Thomas and others, 1981) and proprietary temperature-pressure-spinner (TPS) data obtained by GEOOC are the bases of the following conclusions about temperatures in the "typical" Geysers reservoir:

1. Temperature logs from flowing wells consistently indicate temperatures in the range of 440 to 490°F within the reservoir. Where TPS logs are available, enthalpy values range from approximately 1220 to 1250 BTU/lb.
2. Temperature-depth plots of maximum-reading thermometer (MRT) measurements made on bottom during directional surveys while drilling in the "typical" reservoir usually range from 400 to 450°F with maximum values near 480°F. MRT temperatures exceeding 600°F are the first indication of a high temperature reservoir.
3. Flow line temperatures (FLT) of the circulating drilling medium (air) measured while drilling the "typical" reservoir are normally in the range of 210 to 230°F but may approach 320°F in some cases.

Using the data developed from wells in the "typical" Geysers reservoir, criteria were established to determine whether or not the HTR is penetrated. These criteria are as follows and are ranked by importance:

1. MRT values exceeding 500°F.
2. Downhole flowing steam temperatures exceeding 500°F.
3. FLT measurements of more than 300 to 320°F.

Taken together, these criteria were used to estimate the depth to the HTR for each well drilled by GEOOC. Examples of these criteria and the resulting estimate of depth to the HTR are graphically presented as individual temperature-depth plots for both a "typical" well and a high-temperature well (Figures 5 and 6). Accuracy of the depth estimates to the HTR is about 200 ft for most wells.

The temperature logs of flowing steam from completed wells often do not accurately show the boundary between the "typical" and high-temperature reservoirs. The reason for this is that high-temperature steam flowing up the wellbore masks the cooler entries in the "typical" reservoir (Drenick, 1986). Consequently, MRT values collected while drilling wells serve as a better criteria for delineating the top of the HTR and are ranked accordingly. However, it is acknowledged that MRT values from unequilibrated boreholes are not accurate temperature measurements of the reservoir rock temperatures (Pruess and others, 1987).

Although the maximum temperature of the HTR is not known, a flowing steam temperature of

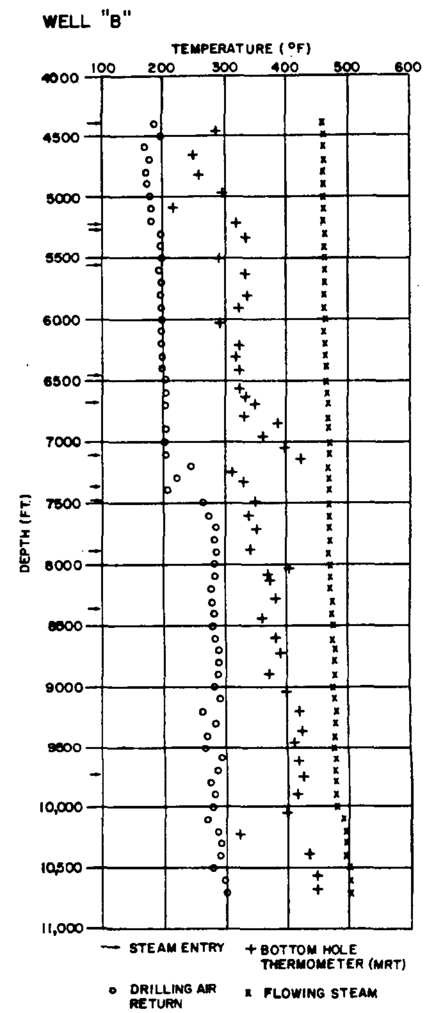


Figure 5: Temperature-depth plot for well penetrating only the "typical" Geysers reservoir.

656°F was measured prior to the failure of one temperature tool. The upper limit is not known because neither thermometers nor electric logging tools are available which exceed about 650°F. Where TPS logs are available, the enthalpies measured in the HTR range from 1300 to 1320 BTU/lb.

The depth to, and areal extent of, the HTR in the area of GEOOC's operation in the Northwest Geysers is shown on Figure 7. High-temperature wells are also known to the northeast (e.g., Occidental Wilson 1 well) but because several deep wells between these two areas encounter only the "typical" reservoir, it is unknown whether or not the two areas tap the same HTR. It is unknown how far the HTR may extend to the northeast, but it could extend across the Clearlake volcanic field (Beall, 1985). Similarly, it is unknown whether or not the HTR is present below the greater Geysers production area and has not yet been detected (Drenick, 1986) because wells and/or temperature measurements may not be deep enough.

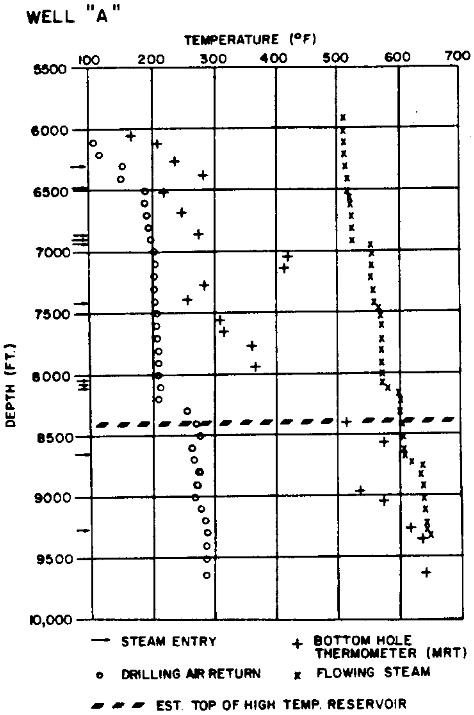


Figure 6: Temperature-depth plot for well penetrating HTR and overlying "typical" Geysers reservoir.

The thickness of the "typical" Geysers reservoir overlying the HTR is shown on the geologic cross section of Figure 2. This section is indicative of the relative contribution that the "typical" reservoir makes to wells penetrating the HTR. The thinnest part of the "typical" reservoir is also where the enthalpy and gas concentration of the steam, as measured at the wellhead, are highest.

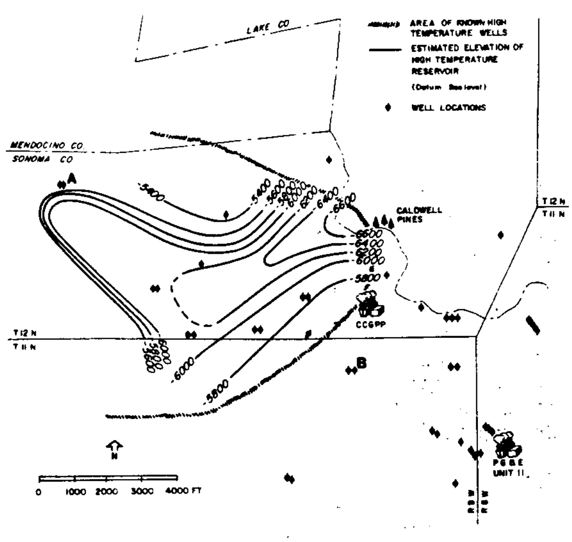


Figure 7: Depth to HTR in GEO portion of Northwest Geysers.

Heat transport from the "typical" reservoir to the surface is largely by conduction (Urban and others, 1975). Within the "typical" reservoir, heat transport is largely by convection (White and others, 1971) as evidenced by almost isothermal temperature-depth relationships. In Figure 5, an illustration of this phenomenon is presented. Heat transport in the HTR appears to have a large conductive component. Although the bottom-hole measurements made while drilling are not equilibrated, there are definite increases in temperature with depth in the HTR with apparent gradients ranging from approximately 5 to 10°F/100 ft. An illustration of an apparently high temperature gradient in the HTR is provided in Figure 6.

For any given heat flux, the temperature gradient is a function of thermal conductivity. Thermal conductivity measurements on 19 samples of hornfelsic graywacke were made using a method described by Sass and others (1971) to determine if the apparent higher temperature gradients observed in the HTR were related to the thermal alteration of the graywacke. Thermal conductivity values of the hornfelsic graywacke samples ranged from 6.1 to 7.6 TCU (mcal/cm-sec-°C) with a median value of 6.8 TCU. These values are very similar to graywacke which has a mean value of 7.6 TCU (Thomas, 1986). Therefore, the apparent high-temperature gradients in the HTR cannot be attributed primarily to contrasting thermal conductivity values.

Pressure Measurements

Pressure profiles were obtained in flowing wells, idle wells on small "bleeds", and completely static wells. The profiles are from wells both inside and outside the HTR shown in Figure 7. Approximately 50 profiles are available from the various wells, with the measurements having been performed from 1 to 600 days after completion of drilling. In all cases, steam is the pressure controlling medium with the maximum pressure measured being approximately 520 psia at sea level datum. All pressure gradients conform to expected steam densities; higher gradients which would be expected for a liquid-dominated section or a boiling, vapor-dominated to liquid-dominated interface have not been encountered. Further, there do not appear to be significant pressure differences between the two reservoirs. Thus, the HTR is not a liquid-dominated region at this time, nor does it appear to have substantial pressure differences from the "typical" reservoir which overlies it. Analysis of pressure buildup data, and other pressure transient measurements is underway to clarify the interpretation of the pressure behavior of the HTR.

Geochemistry of Fluids

Samples of steam were collected at the wellhead or steam line during drilling and flow testing. Drilling samples were collected during trips and directional surveys. The drilling samples represent cumulative samples; i.e., the steam of each succeeding or deeper entry is mixed with the previous entries. Flow test samples represent combined production from all entries. Data from the analyses of noncondensible gas, chloride, oxygen-18 (0-18) and deuterium (D) data can be used to distinguish the HTR and "typical" reservoir.

Samples collected during drilling reflect changes of concentration with depth. A "typical" Geysers well has relatively constant fluid chemistry concentrations in the reservoir (see Figure 8), except for a possible gassy upper layer due to condensation. Gas concentrations in a high-temperature well increase significantly near the top of the HTR (see Figure 9).

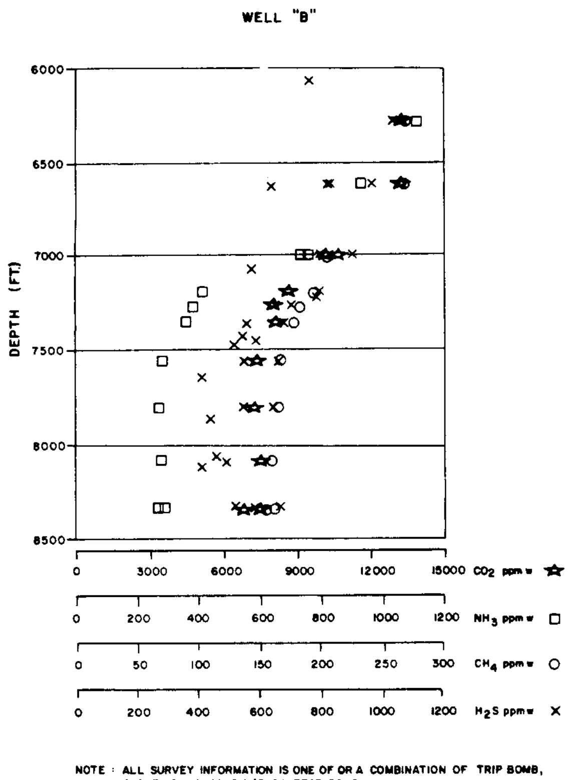


Figure 8: Wellhead gas concentrations of a well penetrating only the "typical" Geysers reservoir.

Flow test results from high-temperature wells representing the combined production of the "typical" and HTR reservoirs are compared with "typical" wells in Table 1. Wells penetrating the HTR contain higher concentrations of noncondensible gas, chloride and to a lesser extent 0-18 and D than "typical" wells. When the gas results are compared to the proportional contribution of the HTR to the total flow, the HTR appears to produce steam with 6 to 9% by weight noncondensible gas and 1900 to 2600 ppmw hydrogen sulfide (H_2S) contrasted to 0.85 to 2.6% and 150 to 800 ppmw, respectively, in the "typical" reservoir. Chloride concentrations in steam at the wellhead from the high-temperature wells range from 15 to 150 ppmw; chloride in HTR steam is estimated to be about 200 ppmw. 0-18 and D are enriched in high-temperature wells relative to the "typical" reservoir but the data are not sufficiently consistent to calculate the isotopic composition of the HTR steam.

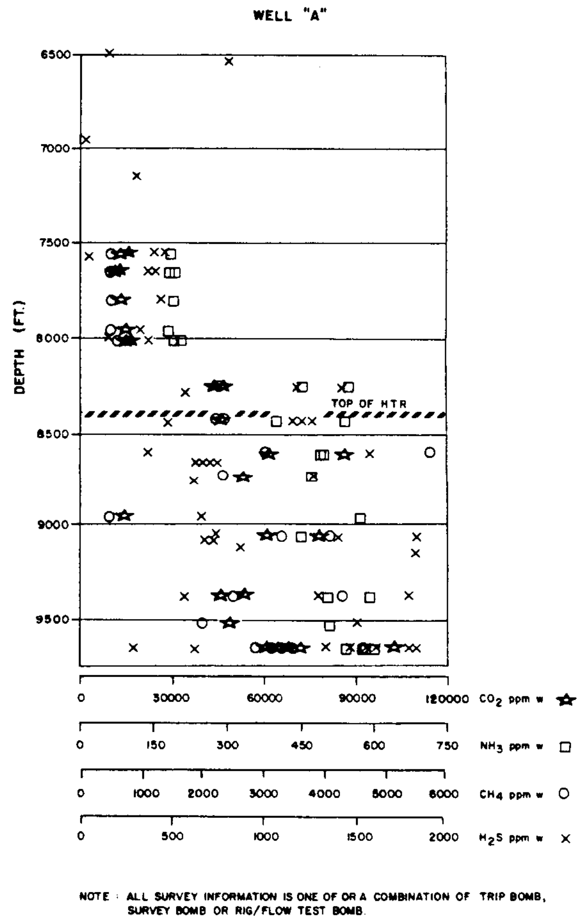


Figure 9: Wellhead gas concentrations of a well penetrating the HTR.

The composition of gas from the HTR is distinguished by enrichment in methane (CH_4) and carbon dioxide (CO_2) and depletion in ammonia (NH_3) and H_2S relative to the "typical" reservoir. However, these differences are small compared to the fieldwide variations in the noncondensible gases across The Geysers (see Figure 4) where noncondensible gas values are almost two orders of magnitude higher in the Northwest than the Southeast (Truesdell and others, 1987).

Similar gas composition and gas concentrations on the same order of magnitude in the HTR and "typical" Northwest Geysers reservoir are consistent with the similar mineralogy between the two reservoirs given that water/rock reactions are the primary control on reservoir fluid chemistry. Variations can be explained by differences in source fluid and temperature. The presence of connate water as suggested previously (Haizlip, 1986), would increase the concentrations of chloride, D and 0-18 in the steam. Higher concentrations of chloride and noncondensible gases (CO_2 and CH_4, in particular), and relatively lower NH_3 can be generated in steam by boiling at higher temperatures. The high gas concentrations in the HTR produce significant partial pressures, possibly over 10 bars (Mahon and others, 1980). This has the effect of lowering and flattening the boiling point to depth curve, partially explaining the change in temperature gradient in the HTR.

EVOLUTION OF THE GEYSERS RESERVOIR

Quaternary felsic intrusives, probably related to the Clearlake volcanics, intruded the Franciscan graywacke and associated rocks (Schriener and Suemnicht, 1980) and are found throughout the subsurface in The Geysers (Hebein, 1986). The intrusions caused heating, uplift, and are a likely cause of fractures in the overlying steam reservoir (Jerome and Cook, 1958; Koide and Bhattacharji, 1975). Uplift in The Geysers initiated deep erosion and landsliding and gave the area a geomorphic signature different from the surrounding areas (Bebber, 1986).

Intrusion probably caused extensive fracture enhancement as well as thermal metamorphism of the graywacke close to the intrusives. Consequently, the five discrete convection cells controlled by fracturing in The Geysers (Thomas and others, 1981) may be a result of localized fracture enhancement by intrusion rather than regional tectonics. Heating of the formation water in the fracture system around the intrusives also initiated (a) hydrothermal system(s). Mineral isotope and other data indicate that a liquid-dominated, high-temperature reservoir pre-dated the present vapor-dominated Geysers reservoir (Sternfeld, 1981). The Quaternary mercury deposits once mined at the periphery of The Geysers (Bailey, 1946) may be the halo around this earlier hydrothermal system.

Where the felsites were intruded sufficiently shallow as in the Southeast Geysers (Hebein, 1986), the associated fracture system reached the surface allowing venting and decompression of the hydrothermal system, beginning boiling and convection. The large, surficially altered, areas in the Southeast and Central Geysers are a record of both past and present degassing of the system.

Compared to other areas in The Geysers, relatively little CO_2 (500± ppmw) and H_2S (50 to 100 ppmw) are presently found in the steam from wells nearest these vent areas (Truesdell and others, 1986). This near-surface fracture enhancement also allowed the entry of meteoric water into the system(s). The present steam reservoir found in the Southeast and Central Geysers is from a vented liquid system that has lost most of its original gas and formation water and is now flushed by meteoric water (Truesdell and others, 1986). The Northwest Geysers is believed to be following the same, but slower, evolutionary development as in the Southeast and Central Geysers. The HTR is a recently vented liquid-dominated reservoir. A "brine" or liquid-dominated system below the HTR cannot be ruled out.

Evolution of the Northwest Geysers reservoir is believed to be slower because the intrusions are deeper; only a few thin felsic dikes are encountered by wells and the hornfels development is deep (below -5900 ft subsea). The fracture system associated with the intrusive(s) therefore is also deeper; consequently, the top of steam is deeper in the Northwest Geysers than other parts of The Geysers where the felsite intrusives are known to be shallow. The top of steam is -2500 ft to -4500 ft in the Northwest Geysers, compared to 2000 ft to -2500 ft in the Central and Southeast Geysers (Thomas and others, 1981). Venting of the deep Northwest Geysers system to the surface may therefore depend upon faults related to regional tectonism and interconnection with other fracture systems in the Central Geysers. The few, relatively insignificant, vent areas in the Northwest Geysers are all associated with faults. Static pressure declines in unproduced GEOOC wells in the "typical" reservoir suggest connection with the fracture system(s) of wells now being produced in the Central Geysers. Because current Central Geysers production may be an artificial vent of the Northwest Geysers, it is reasonable to assume that the area of extensive alteration near Geysers Resort and along Big Sulphur Creek may also naturally vent the Northwest Geysers.

The consequences of a poorer surface connection with the steam reservoir than the Central and Southeastern Geysers areas includes less venting of noncondensible gas and less dilution by meteoric water. The high-temperature reservoir underlying the "typical" reservoir is believed to be simply a fossil of the liquid-dominated system in which the onset of convection is recent, leaving an important conductive element in the transfer of heat from the evolving hydrothermal system.

CONCLUSIONS AND CONCEPTUAL MODEL

1. The enrichment of 0-18 and D in steam from the Northwest Geysers wells previously described by Haizlip (1986) is probably from a connate water component in the high-temperature reservoir (HTR).
2. The single high-temperature well previously described by Drenick (1986) in the Northwest Geysers penetrated a large HTR that may extend beyond the Northwest Geysers.

3. The HTR described in this paper is a transient phenomenon caused by the recent transition from liquid-dominated to vapor-dominated conditions. This is the same conclusion as that suggested by Pruess and others (1987) for high-temperature wells at Lardarello.

The HTR in the Northwest Geysers is probably a deep, evolving system in contrast to the shallower, leaky and mature steam reservoir(s) in the central and southeastern portions of the field. Before natural venting and nearby production caused pressure to decline, the HTR was a liquid-dominated system with some connate water; the connate water being the source of the high gas contents, chloride, and unique isotopic composition relative to steam from a "typical" Geysers reservoir. Therefore, the present boundary between the "typical" reservoir and HTR is a transient, thermodynamic condition due to the recent evolution of a vapor-dominated zone from a liquid-dominated zone which has yet to cool down. It also demarks a previous liquid to vapor interface. Pressure in the two reservoirs is essentially the same because they are in communication with each other. In other words, the temperature change in the HTR is lagging the pressure change.

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